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OCT 77 W E COLBURN, J W CUTLER, R A MARCOLINI
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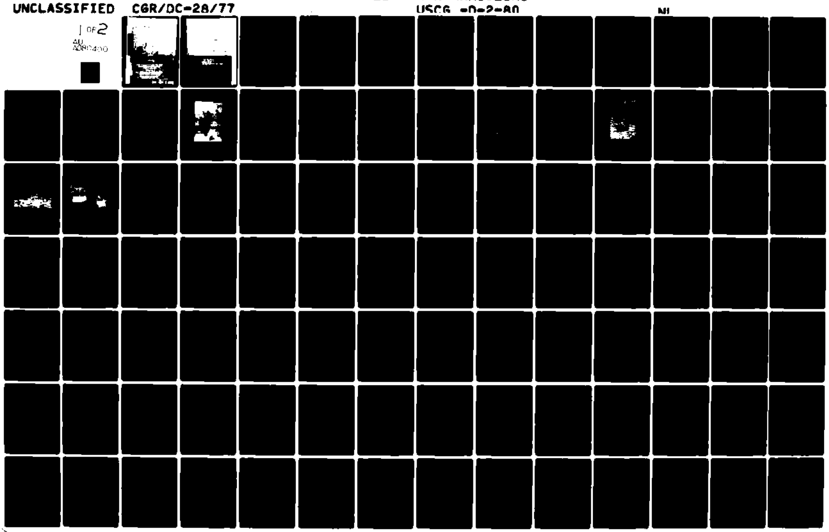

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16. Abstract

Studies were made to determine the horizontal offset incurred by typical Coast Guard sinkers (which are used to moor floating aids to navigation) as they fall from the surface to the bottom of the sea. A series of experiments was conducted in which sinkers were dropped in water and their offsets at the bottom recorded. Included were sinker drops in highly controlled conditions, some of which were recorded on film; and drops from a barge in more typical field conditions.

The effects of the following parameters were considered: sinker size (up to 8500 lbs.), depth of water (up to 102 ft.), height of sinker above water at time of release (up to 6 ft.), current (up to 4 knots), location of center of gravity with respect to the centroid of the sinker, initial tilt of the sinker, and the presence or absence of chain attached.

It is found that offsets generally increase with sinker size and water depth, to a maximum of about 12 feet in still water. The height above water, initial tilt, and presence or absence of chain have small or negligible effects. Some sinkers are found to exhibit a bias in offsets in one direction. The trajectory of the sinker as it falls, and the effect of current on offsets, are discussed from a theoretical point of view and experimental data are presented.

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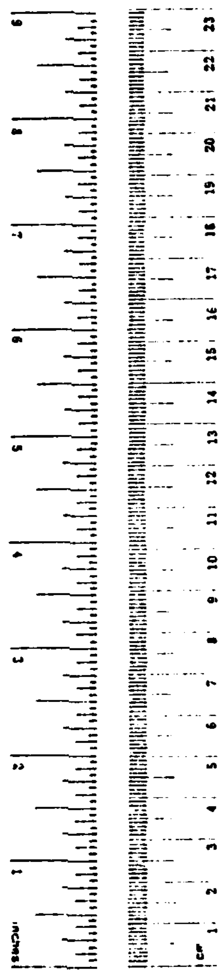
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

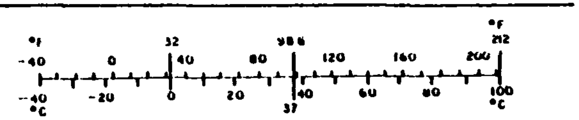
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ABSTRACT

Studies were made to determine the horizontal offset incurred by typical Coast Guard sinkers (which are used to moor floating aids to navigation) as they fall from the surface to the bottom of the sea. A series of experiments was conducted in which sinkers were dropped in water and their offsets at the bottom recorded. Included were sinker drops in highly controlled conditions, some of which were recorded on film; and drops from a barge in more typical field conditions.

The effects of the following parameters were considered: sinker size (up to 8500 lbs), depth of water (up to 102 ft.), height of sinker above water at time of release (up to 6 ft.), current (up to 4 knots), location of center of gravity with respect to the centroid of the sinker, initial tilt of the sinker, and the presence or absence of chain attached.

It is found that offsets generally increase with sinker size and water depth, to a maximum of about 12 ft. in still water. The height above water, initial tilt, and presence or absence of chain have small or negligible effects. Some sinkers are found to exhibit a bias in offsets in one direction. The trajectory of the sinker as it falls, and the effect of current on offset, are discussed from a theoretical point of view and experimental data are presented.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation for the efforts of those who helped in the completion of this report. In particular we gratefully acknowledge the technical and analytical contributions of Analysis and Technology, Inc. of North Stonington, Connecticut. We are also indebted to Mr. Richard Rush and Ms. Betty Mayfield formerly of the U.S. Coast Guard Research and Development Center, for their valuable contributions, particularly in the area of statistical analysis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTATION

A	Cross Sectional Area of Body
C_d	Drag Coefficient on Body
Dt	Descent Time
f_s	Vortex Shedding frequency
g	Acceleration Due to Gravity
Ht	Drop Height
L	Length of Side of Sinker
m	Mass of a Body
m_h	Added Mass in Horizontal Motion
m_v	Added Mass in Vertical Motion
R	Correlation Coefficient
S	Strouhal Number
S.G.	Specific Gravity
Ss	Sinker Size
u	Horizontal Velocity
U	Stream Velocity
v	Vertical Velocity
V_t	Terminal Velocity
W	Weight of Body
Wd	Water Depth
W_w	Immersed Weight of Body
x	Horizontal Displacement
y	Vertical Displacement
σ	Standard Deviation
γ	Specific Weight of Body
ρ	Mass Density of Fluid

1.0 INTRODUCTION

1.1 Background

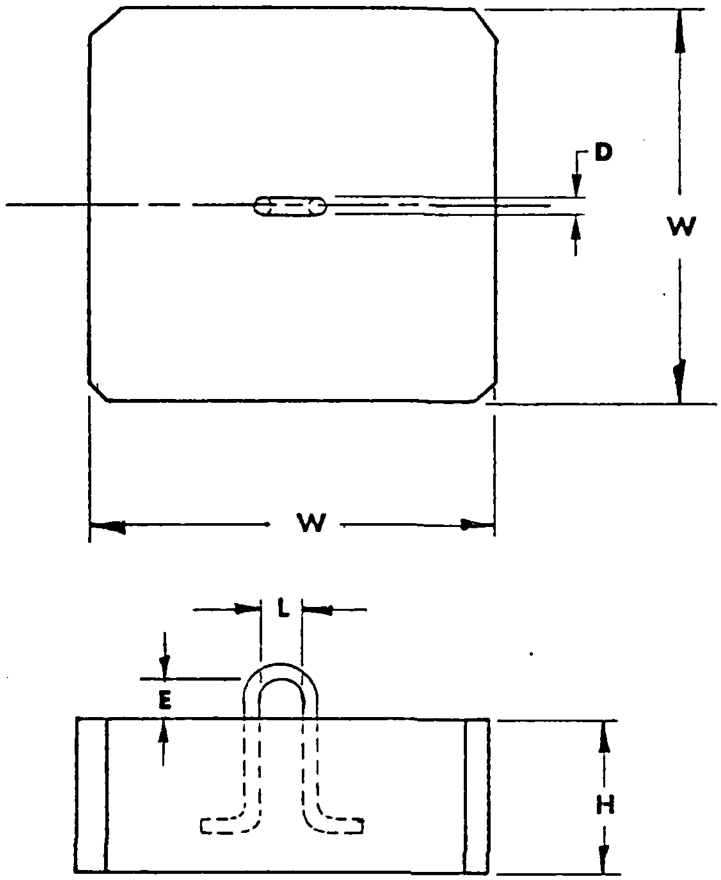
The U.S. Coast Guard is the agency charged by Congress with the responsibility for establishing, operating, and maintaining aids to maritime navigation (Reference 1). Included in this responsibility is the exercise of due care in ensuring that the actual position of the aid itself, and the information advertised to the public by the government, are in concurrence. Among the contributing factors that affect the accuracy with which a navigational buoy is located at the desired position is the horizontal offset incurred by the buoy's sinker from the time it is deployed at the water's surface until it falls through the water column to the seabed. This study was undertaken as a task in the Aids to Navigation Position Accuracy and Reliability (ANPAR) Research and Development Project to assess the extent of error incurred during the sinker's descent in order to determine the significance of this error in relation to other positioning errors.

Figure 1-1 gives the nominal dimensions of standard Coast Guard sinkers, but in practice actual sinkers differ from this considerably in both primary geometrical factors such as length, height and weight, and secondary factors such as rounding of corners and location of centers of gravity. Since all of these affect the hydrodynamic behavior of the sinker, it was felt that complete quantification of the sinker drop problem would be impractical, if not impossible; therefore the following more realistic objectives were aimed for.

1.2 Objectives

The objective of this study was to assess the propensity for a sinker to suffer lateral displacement from its initial drop point in terms of current, sinker weight, water depth, vertical release height and attitude. Specifically, this study attempts to:

a. Assess the effect of current during sinker descent.
b. Examine the trajectory of the sinker as it falls.
c. Determine the nature of the distribution of sinker offsets.
d. Establish a family of error ellipses resulting from horizontal displacement of sinkers during their descent from the water surface to the seabed.
e. Determine the effects of certain major factors such as sinker size and water depth on the above.



WT (lbs)	W	L	H	E	D
12750	60	5.25	42	5.5	2
8500	60	5.25	28	5.5	2
6500	58	5.25	23	5.5	2
5000	54	5.25	21	5.5	2
4000	50	5.25	19	5.5	2
3000	45	5.25	18	5.5	2
2000	40	5.25	15	5.5	1.5
1000	32	5.25	12	5.5	1.5
500	24	5.25	10	5.5	1.5
250	20	5.25	8	5.5	1.5

All dimensions in inches

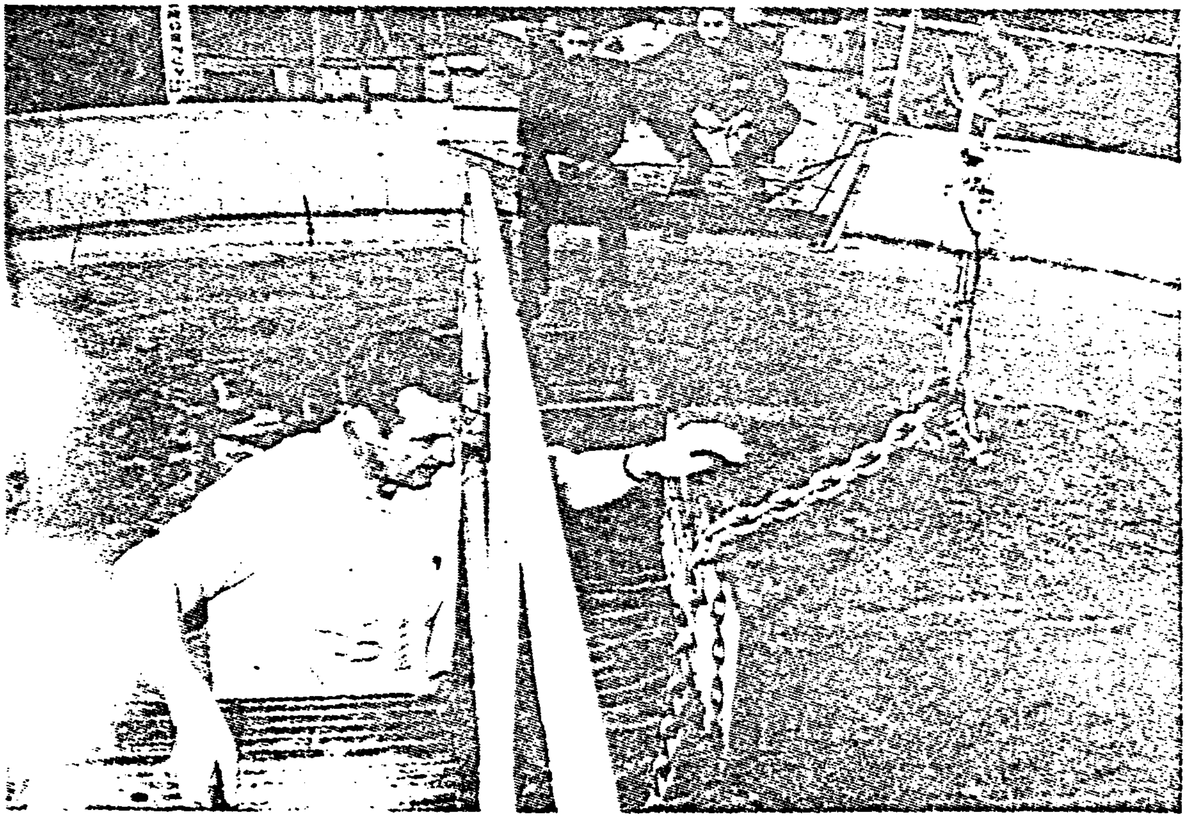
Figure 1-1. Concrete Buoy Sinker Characteristics

2.0 DESCRIPTION OF EXPERIMENTS

A series of experiments were conducted using test facilities at the Naval Surface Weapons Center (NSWC) in White Oak, Maryland, the David Taylor Naval Ship Research and Development Center (DTNSRDC) in Carderock, Maryland, and the Civil Engineering Laboratory (CEL) Port Hueneme, California. The experimental effort was of an iterative nature wherein the first set of experiments conducted during the summer of 1976 at NSWC has the very limited objectives of observing the motion of the sinkers during deployment as a guide for designing future tests and the recording of sinker motion via moving pictures. Additional movies were taken at DTNSRDC in the Circulating Water Channel (CWC) of very small sinkers dropping in currents up to 4 knots. In order to assess the effect of current on larger sinkers, a 250 lb. sinker was dropped from a moving carriage into the Deep Water Basin at DTNSRDC to simulate dropping a sinker from a fixed point into a constant current. After the completion of the movies and observation of the motion from a qualitative standpoint, another test series (second phase) was initated at NSWC with more attention given to the orientation of the sinker. Displacement and directionality observations were recorded for various heights of the sinker above the water, water depths, and initial angles of the sinker to the water surface, as well as the condition of having chain or no chain. One size chain (1/2 inch) was used throughout the testing. These tests were conducted for the larger size sinkers (from 250-1,000 pounds). The 1,000 pound limitation was based upon tank capabilities. The tests run at Port Hueneme were undertaken because of this facility's capability to handle large size Coast Guard sinkers. The tests were run with sinkers from 1,000 to 8,500 pounds in weight. Thus, it can be seen that tests have progressed from initial observations of motion (during which time quantitative tests were being designed) to conducting of quantitative tests in controlled facilities (however, limited as to a maximum sinker size) to the largest size sinker tests conducted in a uncontrolled environment (with a resultant loss in accuracy).

2.1 NSWC Still Water Tank Experiments

The sinkers were dropped in a still water tank located at the U.S. Naval Surface Weapons Center in White Oak, Maryland. This tank is 104 feet deep, 50 feet in diameter, and has an elevator floor which can be adjusted to any depth or raised above the surface for the measurement and removal of the sinkers after a drop test. The sinkers were dropped from a gantry crane located above the tank by the use of a remotely activated electrical release mechanism. A fixed walkway projects over the center of the tank at a height of 4 feet above the water. It was used to orient the sinkers in the desired position prior to drop. Figures 2-1 and 2-2 show the general layout of the test tank. In those tests in which chain was used, the chain was faked out on a wooden pallet 1-1/2 feet above the surface of the water. This pallet was approximately 3-1/2 feet by 4 feet with the boards running perpendicular to the chain faking. All 93 feet of 1/2 inch chain was faked out on the pallet and the end of the chain was secured to the gantry. Figure 2-3 shows that upon release of the sinker the chain streamed off the pallet in a manner



The sinker was positioned in a selected location and orientation. The electrically operated release (shown above the sinker) was actuated remotely and the descent was timed by visual observation through a glass-bottom boat (background).

FIGURE 2-1. POSITIONING OF A SINKER AT THE NSWC TANK

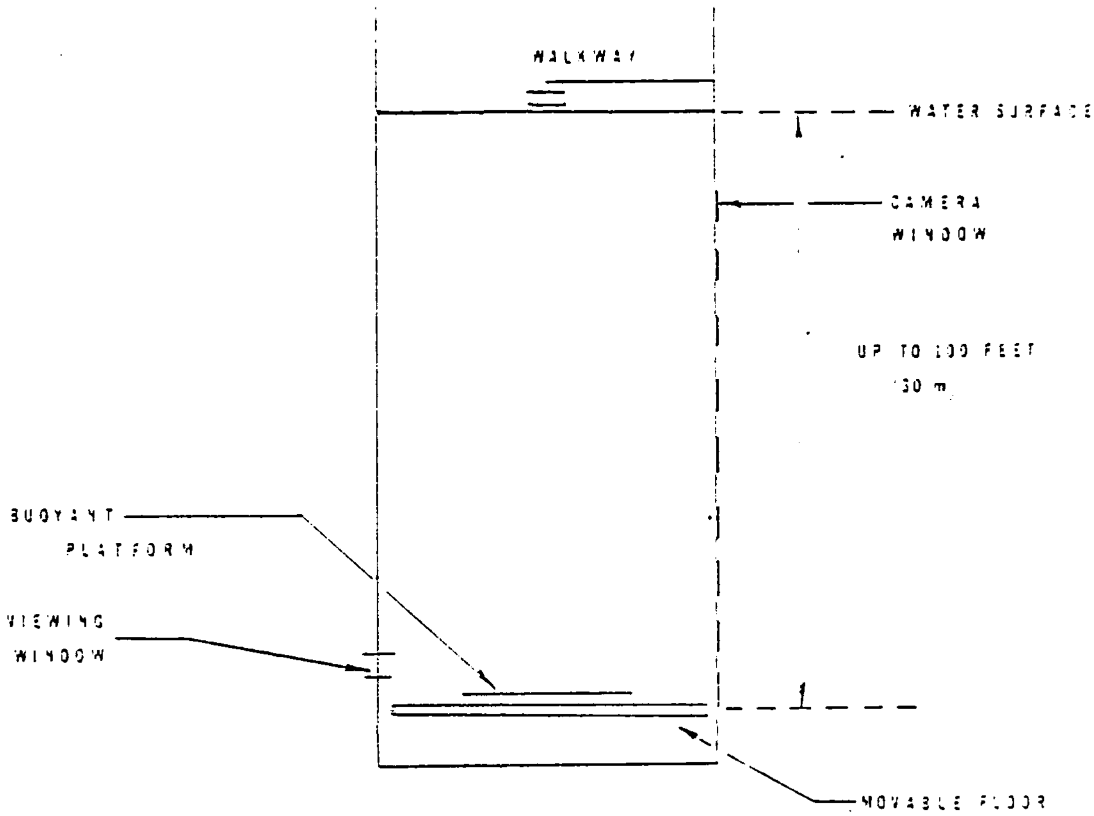


Figure 2-2. 100 FOOT TANK AT NSWC

The chain streamed off the pallet after the sinker's release.

FIGURE 2-3. A SINKER WITH CHAIN IMMEDIATELY AFTER RELEASE

similar to that on a buoy tender in shallow water. (Note: chain is stopped off in deep water as a standard practice; this was not done here.)

2.1.1 First Phase NSWC Experiments

The first experimental phase consisted of dropping various size sinkers into 88 feet of fresh water in the 100 ft still water tank while visual observations were made and movies taken. Sinkers were dropped with and without a constraining chain faked out above the drop point. This was to find whether or not a gross difference in offset and descent velocity existed due to the chain. The drops were timed by means of a stopwatch and movies were taken. The time interval between movie frames was maintained at 1/16 of a second so that the film could be used during analysis to obtain velocity data (displacement-time and velocity-time plots). The camera positions are at 12.5 foot intervals starting 12.5 feet below the water surface. Viewing ports are in similar positions around the tank. A buoyant wooden platform was attached to the moveable floor so as to cushion the impact of the falling sinker.

Each sinker was suspended just above the water surface by means of an electrically operated release. On a signal the release was actuated and the sinker began to fall. Meanwhile a vertical array of movie cameras, one at each of the camera positions mentioned above, was also actuated. The sinker fell approximately along the center line of the tank, and its motion was recorded by each of the cameras in turn. The sinker fell on or near a buoyant platform a few inches above the moveable floor.

The sinkers tested were of similar shape and specific gravity. The shape was that of a rectangular solid with dimensions of width and breadth approximately twice that of each sinker height. The specific gravity of each of the sinkers tested was calculated from the wet and dry sinker weights and found to be very close to 2.4. The physical characteristics of the sinkers used in both the NSWC and DTNSRDC experiments are provided in Table 2-1.

2.1.2 Second Phase NSWC Experiments

During the 2nd phase of the NSWC experiments quantitative measurements of offset and direction were made and the time of descent recorded. Time of descent was measured by visual observation from the water surface through a glass-bottom boat. Qualitative observations of the sinker's trajectory were also made in the boat. A stopwatch was started at the time the electrically operated release was actuated and included the free-fall time for those sinkers that were suspended above the water surface. When possible, more than one sinker drop was conducted for each lowering of the elevator floor in order to reduce test time. The chain was used only on the last drop of the elevated floor sequence in order to prevent the interference of the suspended chain with subsequent drops.

TABLE 2-1. PHYSICAL CHARACTERISTICS OF THE NSWC SINKERS

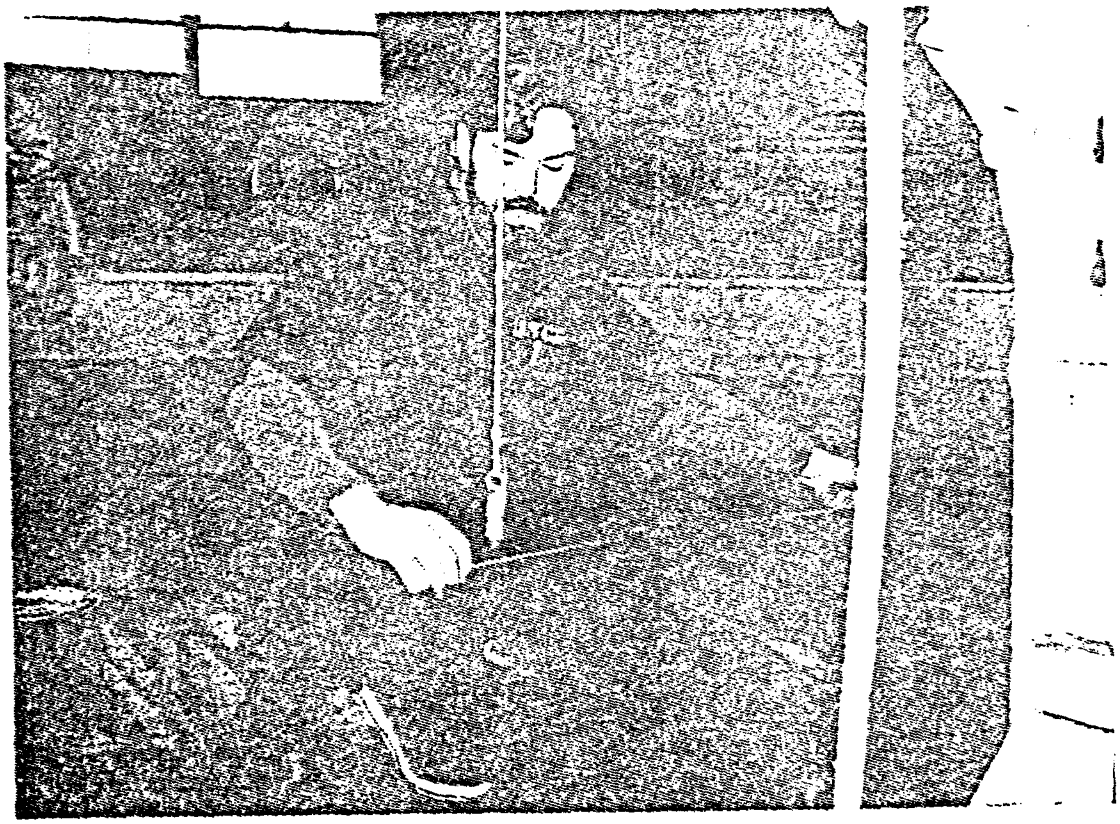
SINKER NUMBER	TYPE*	AIR WEIGHT (lbs)	WATER WEIGHT (lbs)	LENGTH (in)	HEIGHT (in)	SPECIFIC GRAVITY	TAPER
1	E	482	280	24.0	9.8	2.39	NO
2	E	525	307	24.0	10.8	2.41	NO
3	D	302	177	NOT	USED	2.42	YES
4	D	267	160	18.3	9.8	2.50	NO
5	F	1090	635	31.9	12.6	2.40	NO
6	E	490	287	24.0	9.8	2.41	NO
--	A	2.5		4.0	2.0	2.4	NO
--	B	16		8.0	4.0	2.4	NO
--	C	60		12.0	6.0	2.4	NO
--	X	11.2		4.0	2.0	11.4	NO

Excluding Type X sinker: $\overline{S.G.} = 2.41$ $\sigma = 0.03$
*Designation for the purpose of this study.

If a collision occurred and the descending sinker moved a sinker already on the bottom, the data were not recorded and the test was repeated. If, after collision, the descending sinker settled to the bottom without significantly affecting either sinker position, the data was recorded and the hit was noted on the data form next to the second sinker measurement, and is indicated in Appendix B by "H".

When the last sinker was dropped during a series, a plumb bob was suspended from the crane hook and the elevator floor was raised. This enabled the direct horizontal measurement of the offset using the plumb bob as a reference point as shown in Figure 2-4. The precision of this measurement was better than plus or minus one inch.

Each drop from a horizontal plane was selected so that the sinkers would have a varied angular (azimuthal) orientation both with respect to the tank and with respect to the chain. The azimuthal direction of the sinker with respect to a mark on the sinker (on the top surface in an arbitrary corner) before the drop was recorded. After dropping the sinker, its offset and direction with respect to the original position and orientation of the sinker were recorded. The release procedure and drop time were as in Phase I. Sinker drops were randomized so that all drops of a set (one water depth, sinker size, drop height) would not follow each other in order to prevent any influence on a complete set by some transient effect.



The tank's elevator floor was raised after the last drop and the horizontal offset from the release location was measured.

FIGURE 2-4. MEASURING THE HORIZONTAL OFFSET OF A SINKER

2.2 DTNSRDC Current Speed Experiments

The objective of the DTNSRDC experiments was to find the offset from the release point of the sinker as a function of current speed and sinker size. In the first phase, sinker Types A & B were dropped into a circulating water channel. In the second phase, a Type D sinker was dropped from a moving carriage into the Deep Water Basin to simulate dropping a sinker from a fixed point into a constant current. This was done because the large sinker would cause damage if dropped into the Circulating Water Channel (refer to Appendix A for details of the DTNSRDC experiments not included in this section).

2.2.1 Circulating Water Channel (CWC)

The circulating water channel has a fixed drop point and moving current. Its working section is sketched in Figure 2-5. The CWC is 9' deep and 22' across. The flow was varied from 0 to 2 knots. The horizontal flow velocity is constant to within 3% along a vertical line through the center of the channel. An example of the current profile is shown in Figure 2-6. The sinkers were released from a walkway suspended over the center of the channel. The sinkers were dropped with the bottom being about 1" above the water surface, and the drops were filmed from two viewing ports in the side of the channel. The sinkers fell on or near a buoyant platform anchored to the floor. The time of descent was measured and the point of impact noted. The resulting movies were analyzed in the same manner as those taken during the first phase of the NSWC experiments.

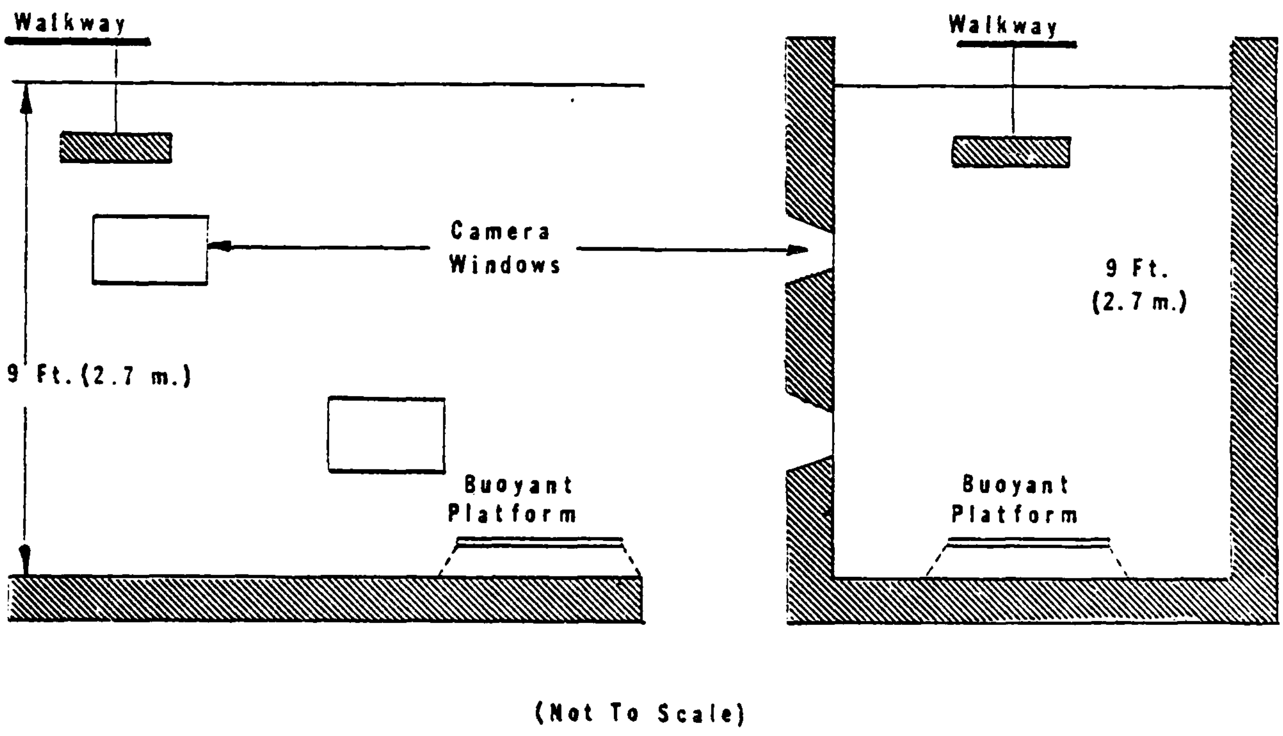


FIGURE 2-5. SIDE AND FRONT ELEVATION OF CIRCULATING WATER CHANNEL

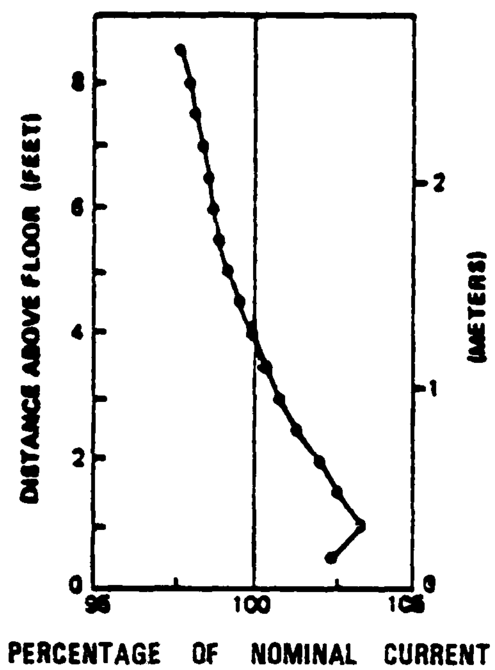


Figure 2-6. Vertical Current Profile in the Circulating Water Channel

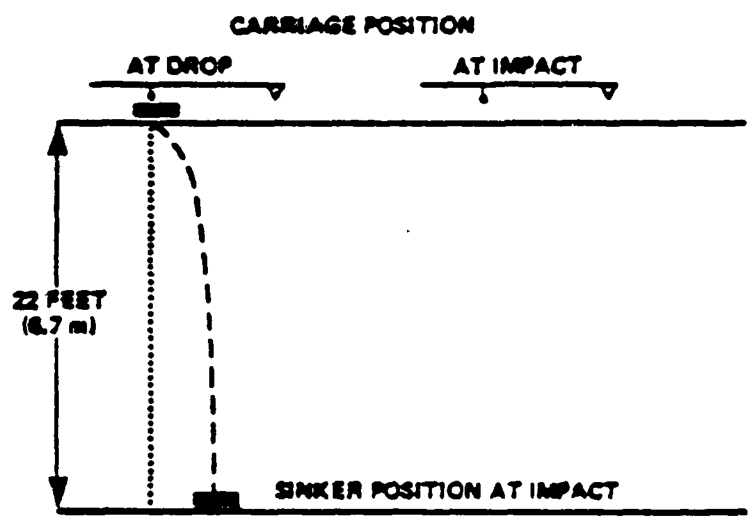


Figure 2-7. Sinker Drop Into Water Basin

2.2.2 Moving Carriage in Deep Water Basin

The second phase of the DTNSRDC tests consisted of 13 drops of a Type D sinker into 22' of water from a moving carriage moving at speeds up to 2 knots. The drop was from a height of about 3" and the resulting velocity was less than the terminal velocity of the sinker. The concept is illustrated in Figure 2-7. At the moment of release of the sinker, the position of the moving carriage was noted. This was accomplished by observing the position of a pointer fixed to the carriage relative to a scale fixed to the side of the towing basin. After the carriage was brought to a stop, it was backed up to a position at which the sinker was released. A thin wire rope with a locating float had been attached to the sinker before the drop. This was now pulled taut vertically and the horizontal offset from the point of release was measured. The precision with which the offset was estimated was approximately ±3" based on careful sighting of the pointer by a second observer.

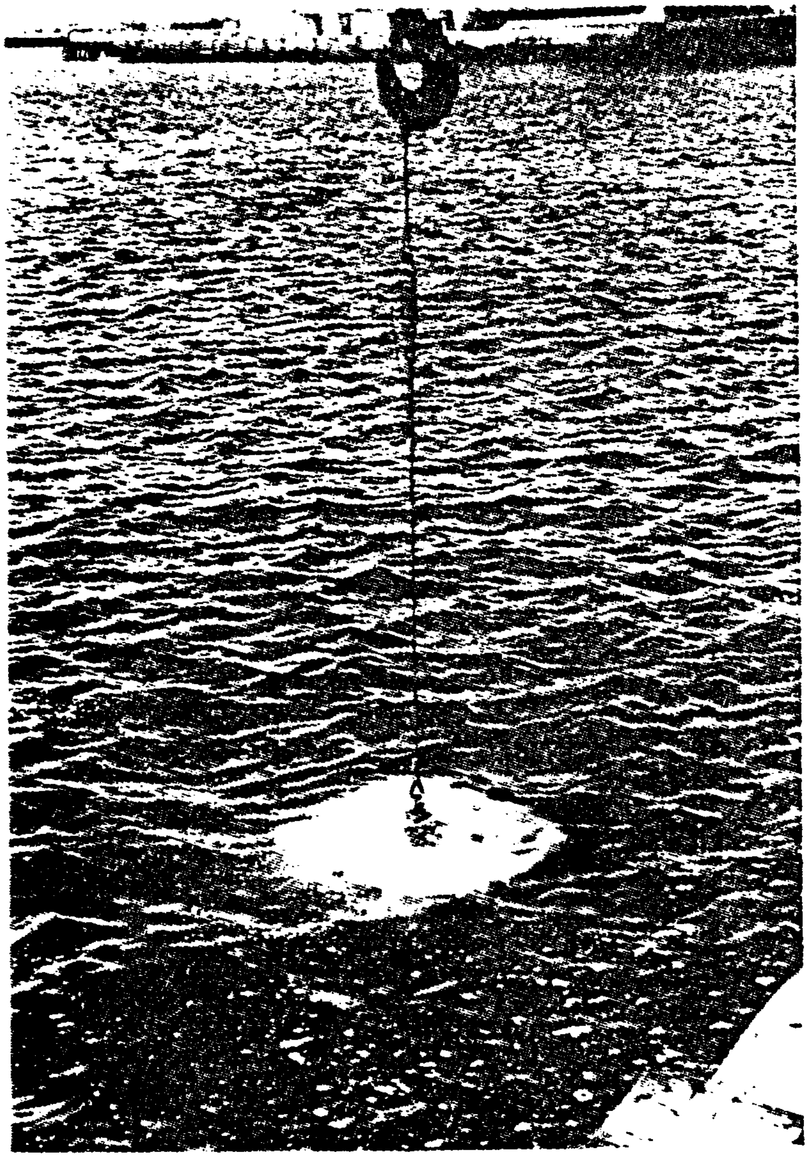
2.3 Full Scale Tests at CEL Port Hueneme, California

Fifteen sinkers, five of each different size (1,000, 5,000 and 8,500 lbs.) were used in the full-scale tests. The sinkers were made specifically for this experiment and contained only concrete and thus were free from old chain. (Old sections of chain are frequently added to concrete sinkers during construction in order to increase sinker density.) It was thought that these sinkers would be more homogeneous than those utilized in the NSWC tests (see Section 2.1).

Before testing began each sinker was numbered, measured, and weighed both in air and in water as shown in Figure 2-8. This information is presented in Table 2-2. Sinker No. 9 was rejected for test purposes because the bale was sufficiently off center to cause a severe tilt in the sinker when it was suspended.

The remaining fourteen sinkers were dropped in water depths of 24, 56, and 88 feet from drop heights as measured from the sea surface to the center of the sinker of 0, 4, and 6 feet. Thus the experiment contained three independent variables; sinker size, water depth, and drop height. A plumb bob was suspended from the release point to the bottom and divers were used to measure the offset and direction of the sinker from the plumb bob. All directions were from magnetic north and there was no attempt to note the orientation of the sinker relative to any identifying mark on the sinker. That is to say, no horizontal orientation of the sinker relative to its release location was made for these tests. Because empirical tests had previously indicated that chain did not significantly affect the offset of the sinker, chain was not used in these tests.

Divers were used to measure the offset distances and directions on the bottom. In order to optimize diver down time, between 5 and 7 sinkers were dropped before the divers entered the water to collect the offset data. This number of drops appeared to make the best overall use of the diver's time.



Before testing began, each sinker was weighed both in air and in water so its specific gravity could be determined. The weight of each sinker was measured by a calibrated load cell located just below the crane hook.

FIGURE 2-8. MASS AND SPECIFIC GRAVITY DETERMINATION OF A SINKER

TABLE 2-2. PHYSICAL CHARACTERISTICS OF THE CEL SINKERS

SINKER NUMBER	AIR WEIGHT (lbs)	WATER WEIGHT (lbs)	LENGTH (in)	WIDTH (in)	HEIGHT (in)	SPECIFIC GRAVITY
1	8200	4500	57 1/2	54 1/2	28 1/2	2.22
2	8200	4500	54 1/2	57 1/2	28 3/4	2.22
3	8250	4600	54 1/4	57 1/2	28 3/4	2.26
4	8200	4600	57 1/2	54 1/2	28 1/2	2.28
5	7900	4350	55 1/2	54 1/2	28 1/4	2.23
6	5800	3300	53 3/4	57 3/4	21 1/4	2.32
7	5600	3300	53 1/2	57 1/2	21 1/4	2.43
8	5600	3200	57 3/4	53	21 1/2	2.33
9	5600	3250	57 1/2	52	21 1/4	2.38
10	5600	3150	57 3/4	51 1/2	21	2.29
11	950	540	30 1/4	30 1/4	12	2.32
12	890	500	30	29 3/4	11 3/4	2.28
13	960	530	29 3/4	30	11 1/2	2.23
14	960	550	30	29 3/4	11 3/4	2.34
15	980	580	30 1/4	30 1/4	12	2.45

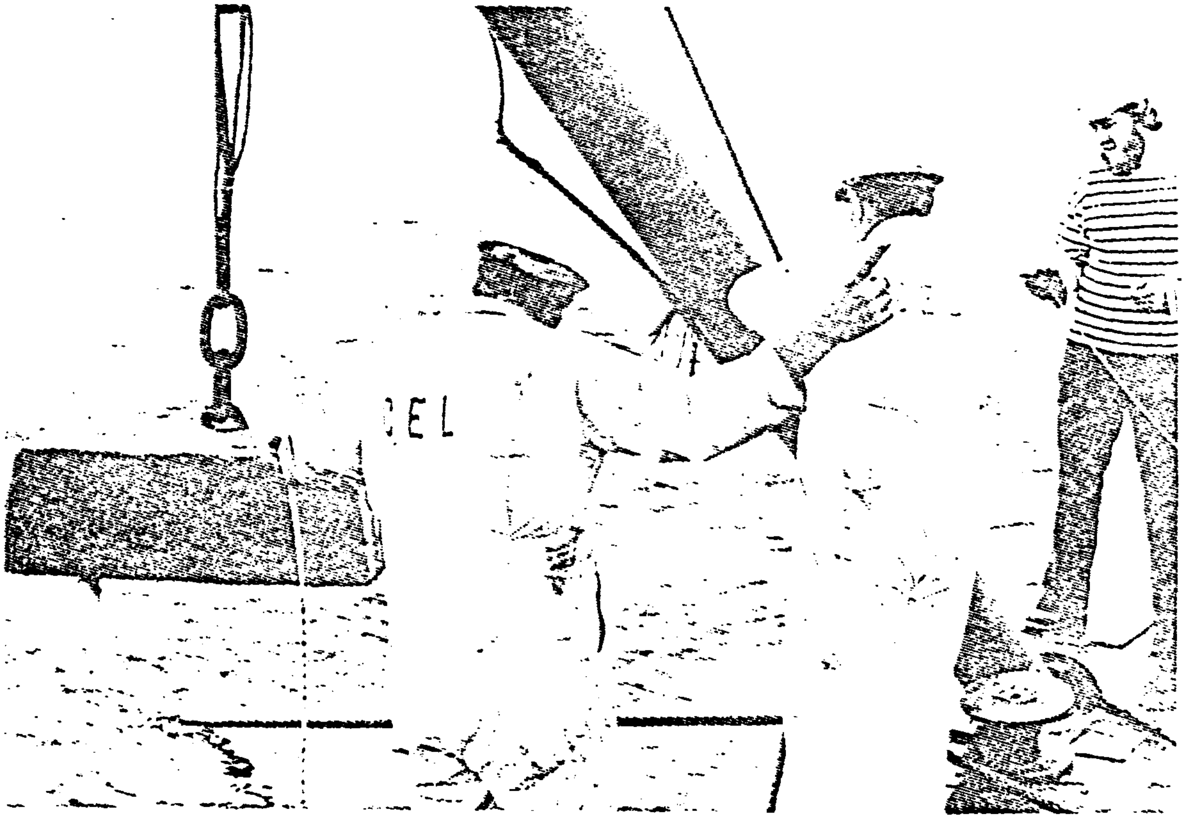
$\overline{S.G.} = 2.31 \qquad \sigma = 0.07$

Due to the handling problems with the large sinkers, as well as the need to re-rig the releasing hook location each time a different size sinker or drop height was used, very little randomness was employed in the performance of these tests. Had randomness been employed the time necessary, and hence the cost of these tests, would have been greatly increased.

Visual observations were made using a face mask, but these were severely impaired by murky water, below a depth of 20 feet. For this reason descent times were determined by using a small piece of parachute cord to the sinker and allowing this line to pay out through one's hand (with gloves on) during descent as shown in Figure 2-9. By keeping a slight tension on the cord, one was able to feel when the sinker struck the bottom. A stop watch was used to measure the time interval from release until touchdown. This parachute cord, however, in no way affected the trajectory of the sinker.

It was intended that this test be conducted in current conditions between 0 and 1 knot. Unfortunately, the test plan was not able to be carried out because there was no noticeable current found in the waters around Port Hueneme at the time of the tests.

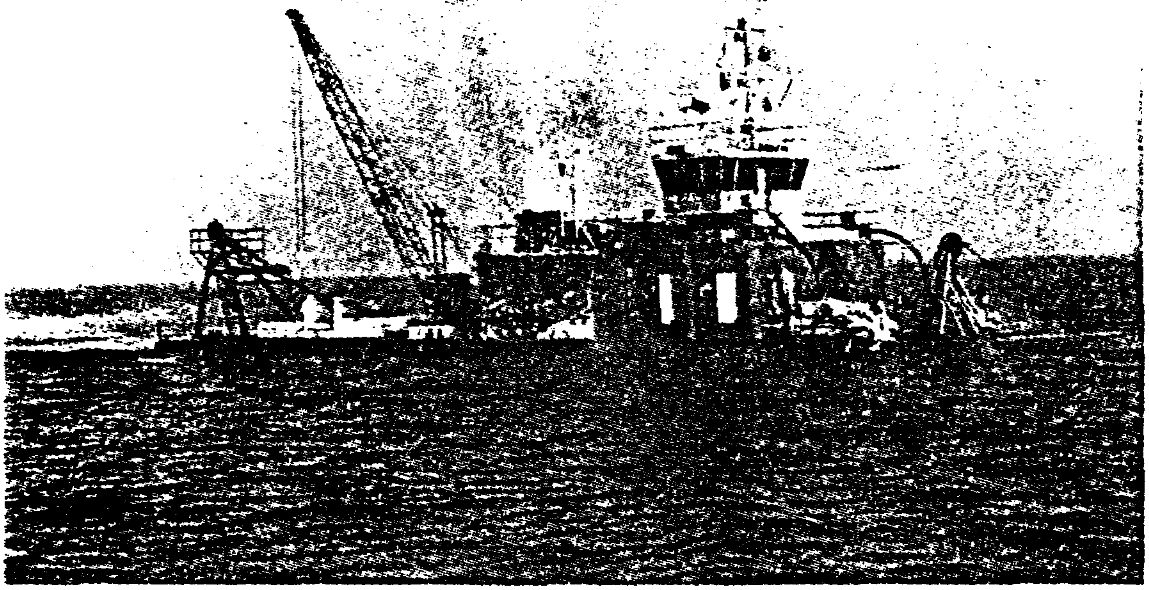
The accuracy of offset distances and directions measured was affected by the sea conditions present at the time of the drop and the possible striking of a previously dropped sinker by one falling to the bottom. Even with the CEL warping tug (shown in Figure 2-10) from which these tests were performed, in a tight 3-point moor the plumb bob might swing in a pendulum motion several feet across the bottom. Furthermore, due to swell conditions the warping tug itself might move a distance of up to 1 foot; thus



Before release each sinker was carefully positioned so the proper height above water was maintained. A sinker's time of descent was measured by attaching a piece of parachute chord to the sinker and by keeping a slight tension, one could "feel" the sinker strike the bottom.

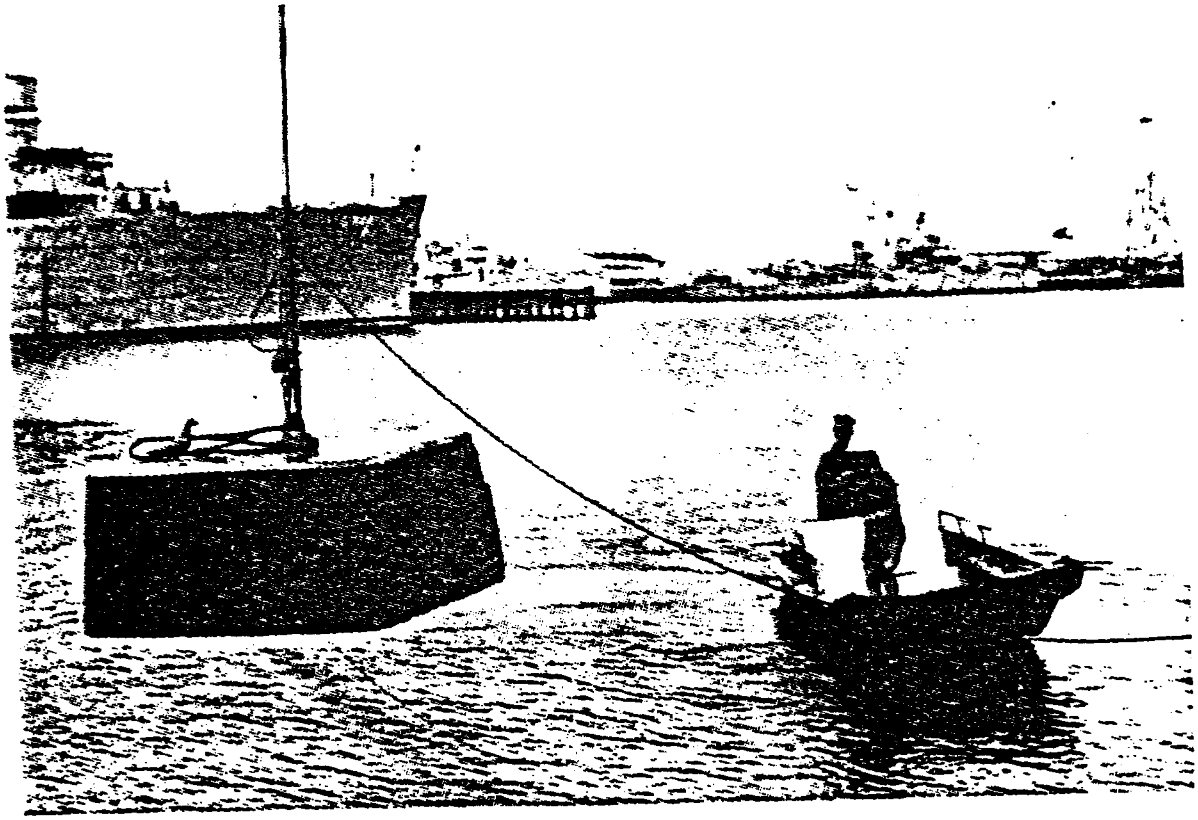
FIGURE 2-9. A 1000 POUND (454.5 Kg) SINKER IMMEDIATELY PRIOR TO RELEASE

the variability of this surface drop location is ±6". In addition, despite the results predicted by an empirical model, sinkers landed on top of one another in nearly every series of drops. Such incidences undoubtedly affected some offset measurements and directionality measurements. A rough estimate of accuracy would be ±1 foot for offset and $\pm 3^{\circ}$ for direction for the 56' and 88' drop cases. Sinker drops made at the 24' depth were done from a crane on a pier in Port Hueneme Harbor (see Figure 2-11). In this case the offset distances were estimated to be on the order of ±4". In all cases the time of descent measurements were estimated to be accurate to approximately ±0.2 seconds. Drop height measurements had an estimated accuracy due to the sea condition of ±3". Water depth measurements due to sea conditions as well as changing tidal levels were accurate to +1 foot and -2 feet.



The C.E.L. Warping Tug from which much of the full-scale testing was performed.

FIGURE 2-10.



An 8500-pound (3864 Kg) sinker just prior to release in Port Hueneme Harbor. Note the stopwatch in the right hand and parachute chord in the left hand of the hard-hatted observer used for time of descent measurements.

FIGURE 2-11. An 8500-POUND (3864 Kg) SINKER BEING READIED FOR RELEASE IN PORT HUENEME HARBOR

3.0 STATISTICAL ANALYSIS OF DATA

This section presents the results of the data analysis, and the statistical methods used. Charts and calculations are included where appropriate. The following general statements apply throughout the section.

All statistical testing is done at 95% confidence. Thus, a "significant" result in an Analysis of Variance (ANOVA) is one whose associated F-statistic reaches the .95 ordinate on the F distribution curve, and a similar remark holds for t-tests. All confidence circles presented contain 95% probability. All null hypotheses are tested at the level .05: therefore, when a null hypothesis is rejected, this is done with "95% confidence". When a test result is less than 95%, but still seems worth mentioning, this is clearly indicated. Finally, where any possibility of confusion exists, the exact confidence level will be indicated.

In testing an hypothesis on a group of data such as the NSWC or CEL experiments, which are divided into blocks of a few (2 to 10) data points each, the test can usually be applied in two ways. First, the data taken as a whole is tested, and then the individual blocks. If 10 blocks (for instance) taken together do not reject the hypothesis, then as many as two individual blocks may reject it due to chance variations between the blocks without contradicting the overall result. In this case it cannot be said that these two reject, while the others do not, unless there is a reason for isolating those blocks independent of the data analysis. Therefore, the statement "The NSWC data does not reject the hypothesis" will be used to mean: the data as a whole does not reject, and no more individual blocks reject than would be expected by chance, assuming the hypothesis to be true. Similar comments apply to such statements as "The CEL data rejects the hypothesis", etc.

X-Y plots of the NSWC sinker drops are given in Figures 3-1 through 3-5 and the CEL drops are given in Figures 3-6 through 3-8. Figures 3-9 through 3-11 show the CEL offsets for each individual sinker, broken down by water depth. Reference to these plots will clarify many of the points discussed in the following sections.

3.1 Offset Distribution in Still Water

Theoretically, it was expected that the following would be true. Each was tested as a null hypothesis at the .05 level, and not rejected by either the NSWC or CEL data. Therefore, they are assumed true throughout the analysis.

1. Both X and Y data are normally distributed. This was established using the Kolmogorov-Smirnov test statistic. The result implies that the data follow the bivariate normal distribution, whose density function is:

$$f(x,y)=\frac{1}{2\pi_x\sigma_y\sqrt{1-R^2}}\exp\left[\frac{-1}{2(1-R^2)}\left(\frac{(x-\mu_x)^2}{\sigma_x^2}-\frac{2R(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y}+\frac{(y-\mu_y)^2}{\sigma_y^2}\right)\right]$$

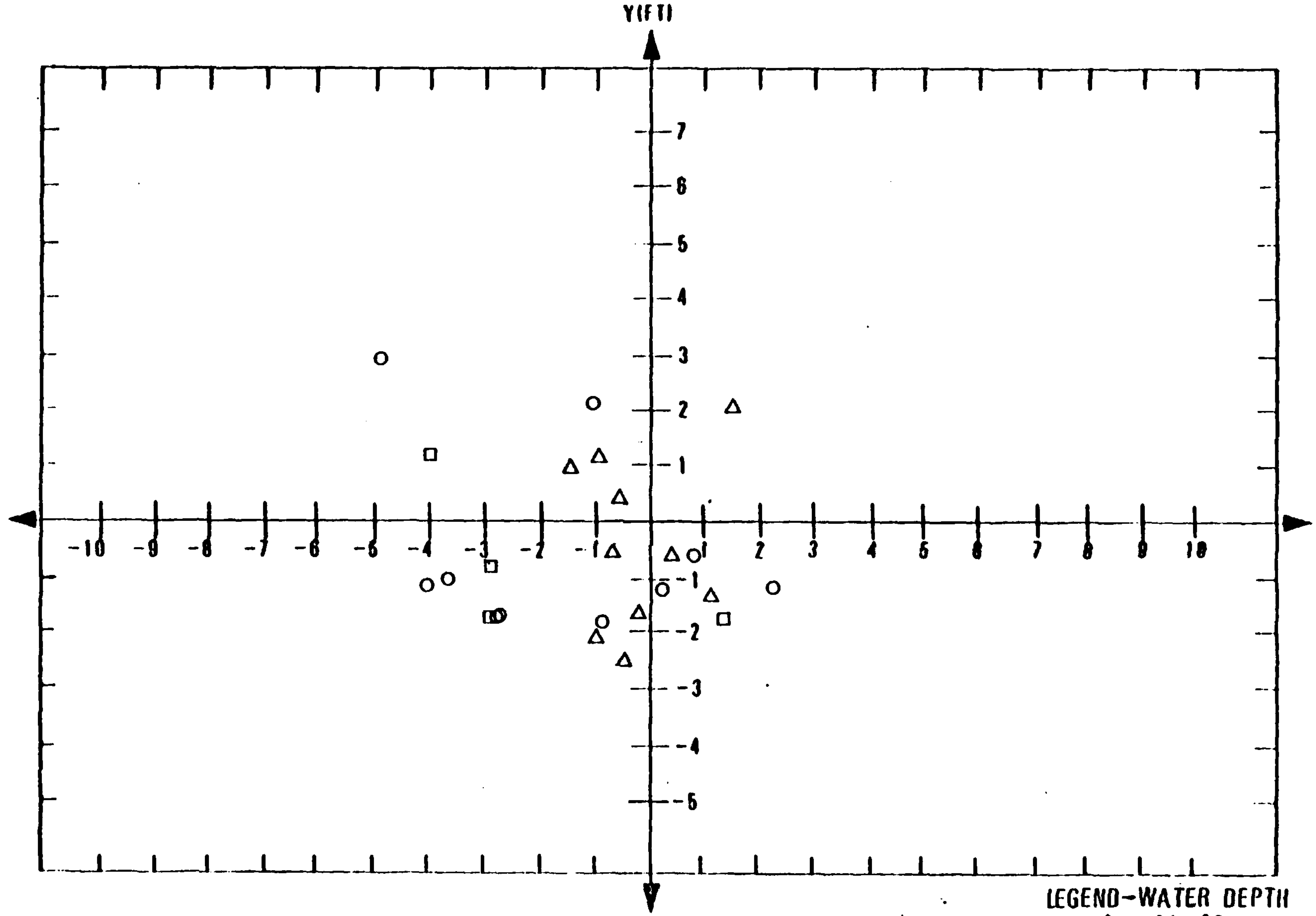


FIGURE 3-1 NSWC SINKER OFFSETS FOR SINKER #4 (250 LBS)

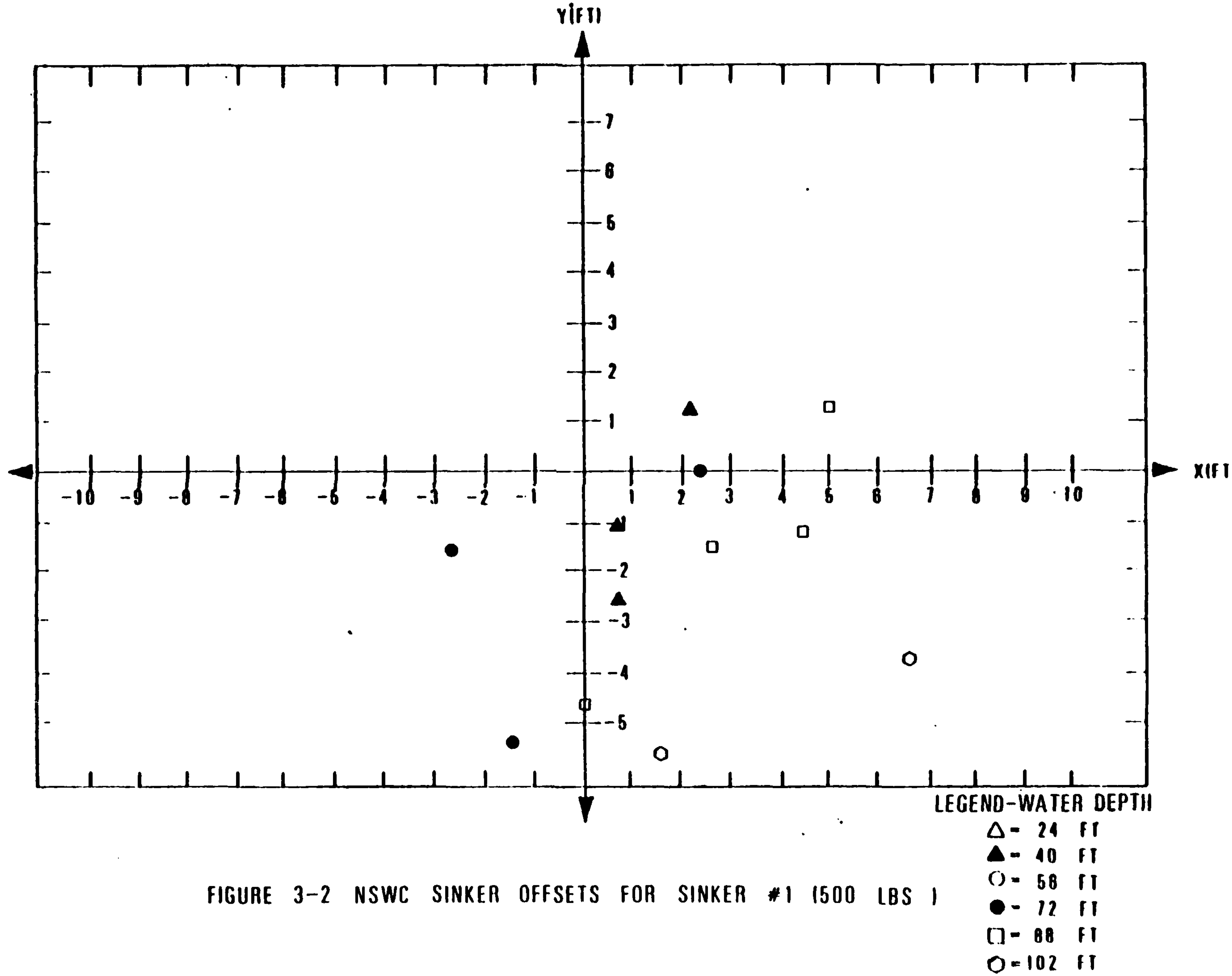


FIGURE 3-2 NSWC SINKER OFFSETS FOR SINKER #1 (500 LBS)

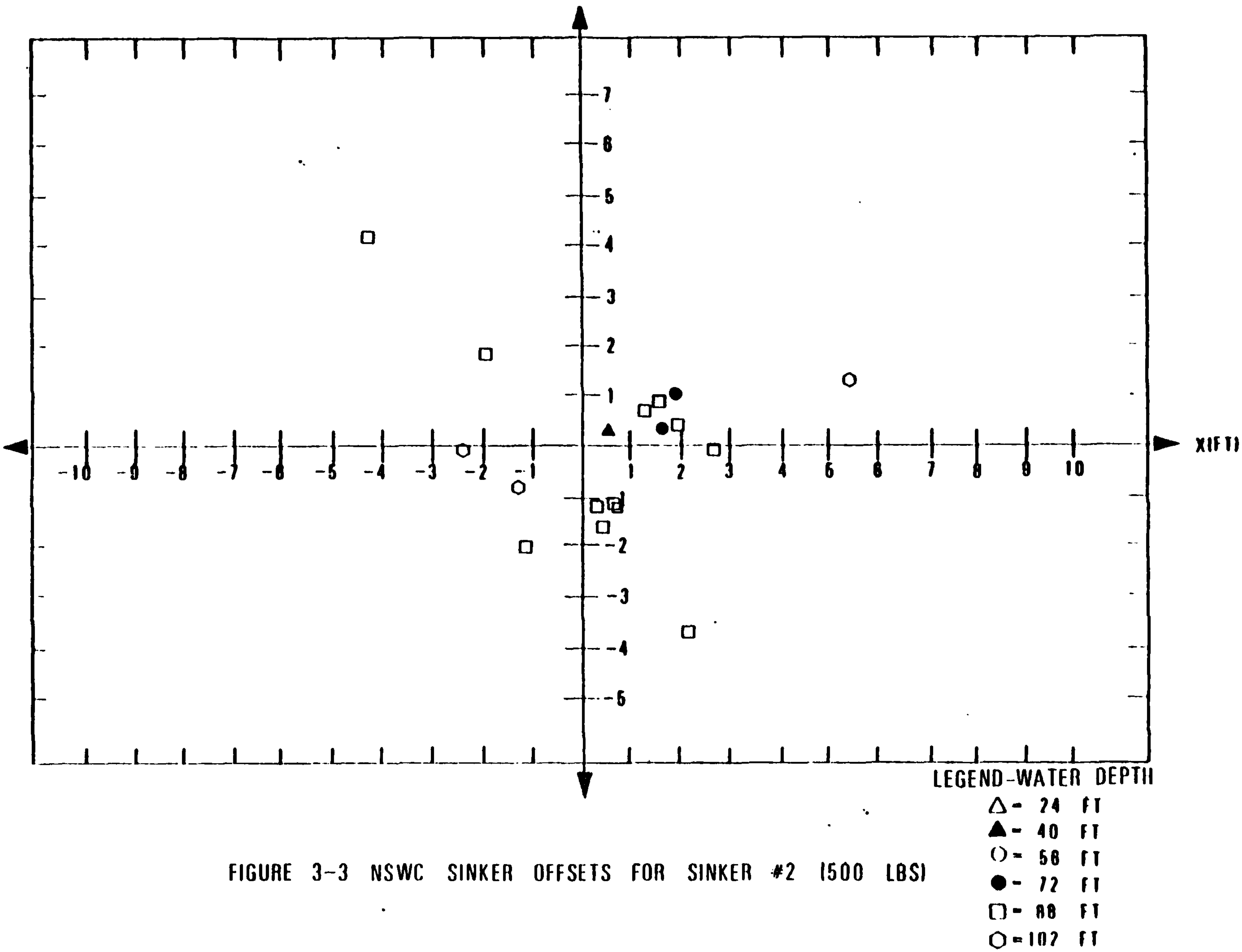


FIGURE 3-3 NSWC SINKER OFFSETS FOR SINKER #2 (500 LBS)

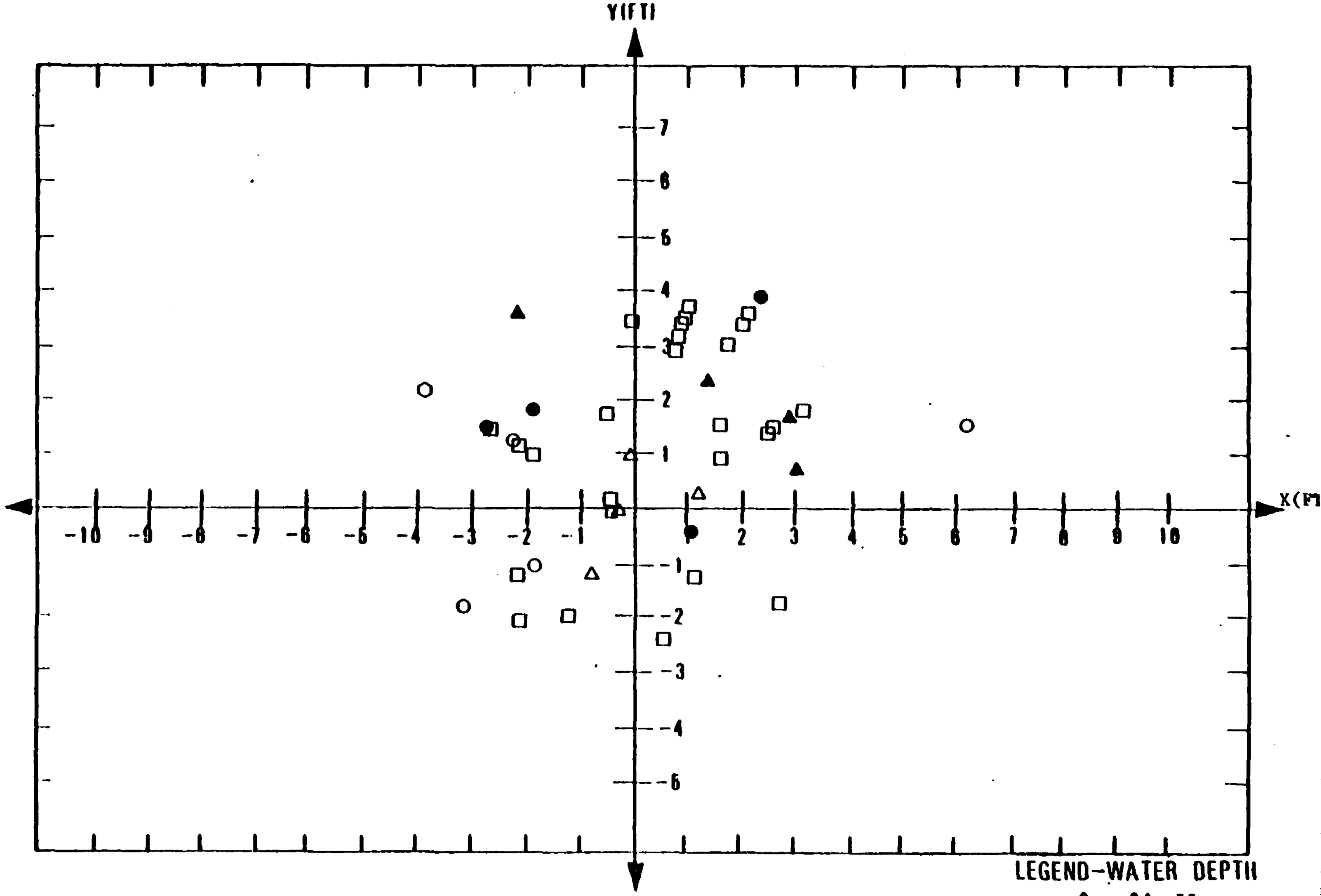


FIGURE 3-4 NSWC SINKER OFFSETS FOR SINKER #6 (500 LBS)

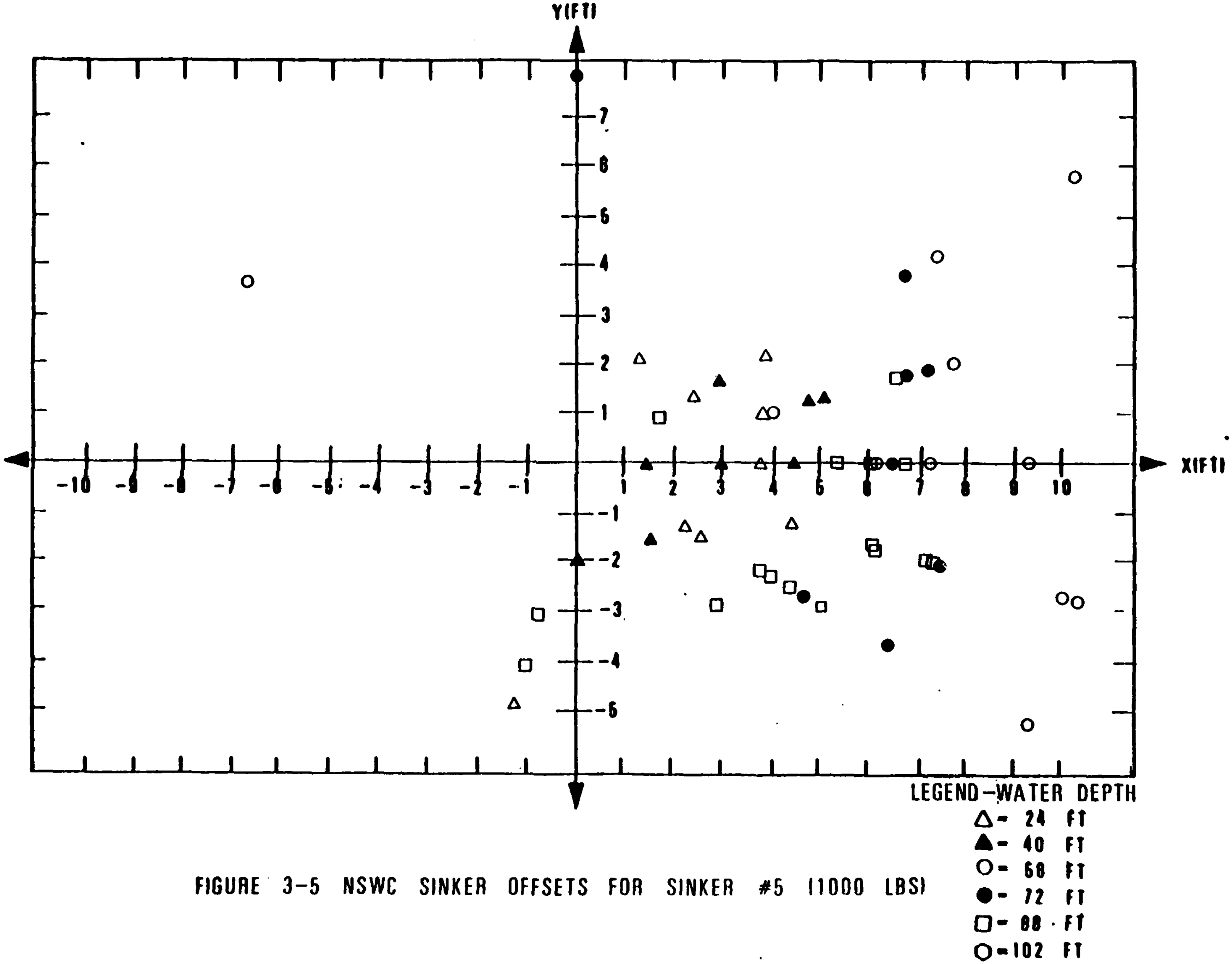


FIGURE 3-5 NSWC SINKER OFFSETS FOR SINKER #5 (1000 LBS)

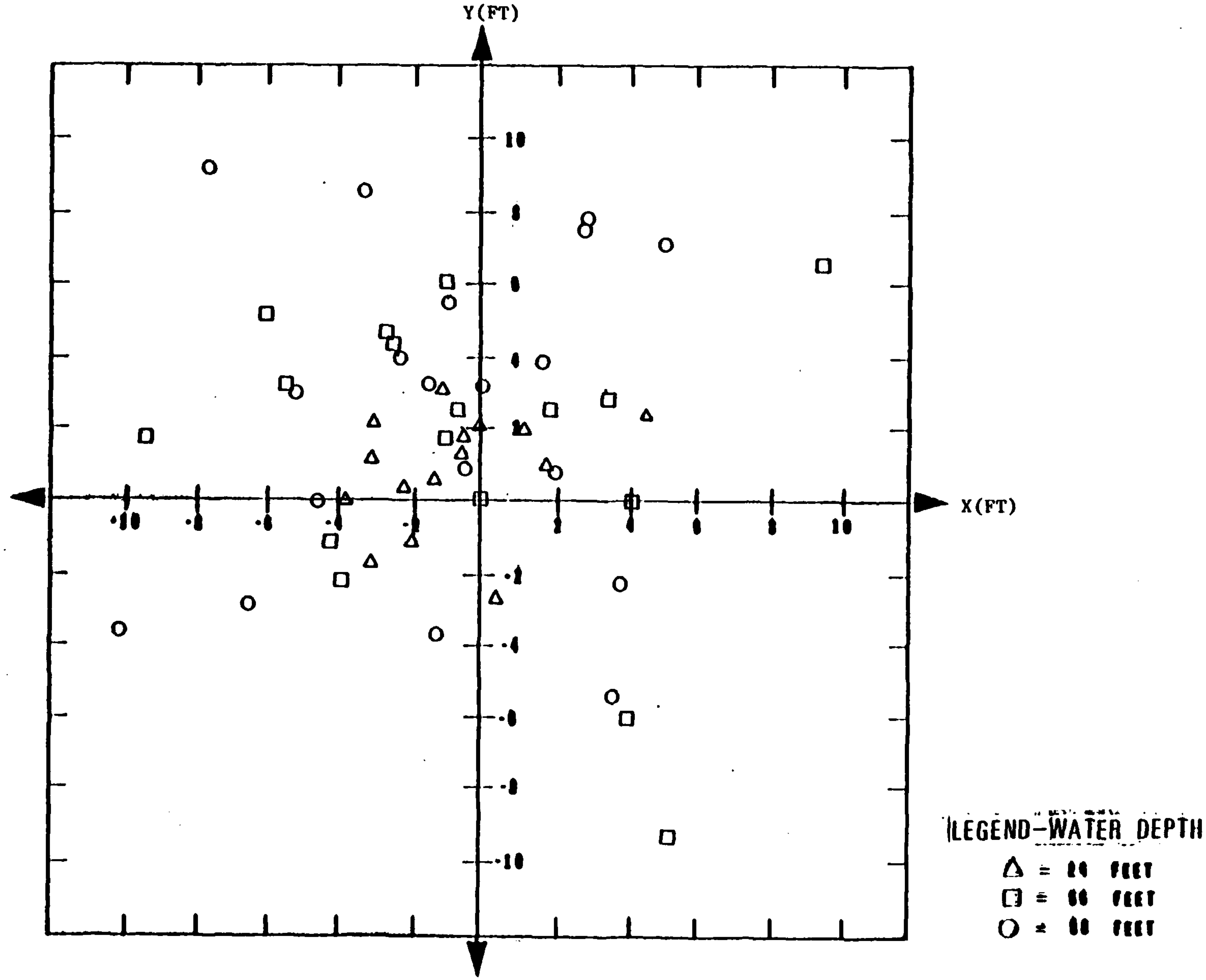


FIGURE 3-6 PORT HUENEME (CEL) SINKER OFFSETS FOR 1000 LB SINKERS

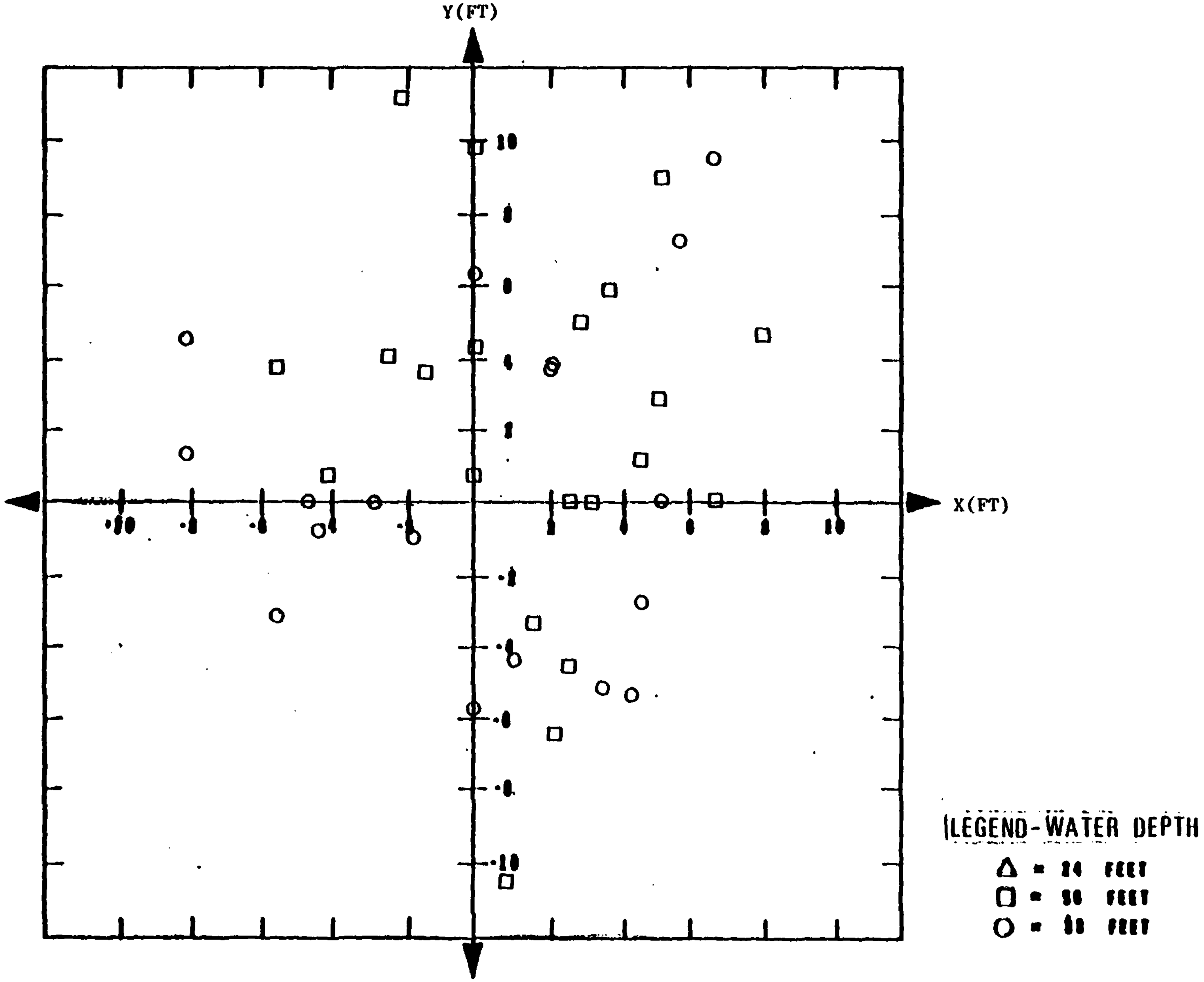


FIGURE 3-7 PORT HUENEME (CEL) SINKER OFFSETS FOR 6000 LB SINKER

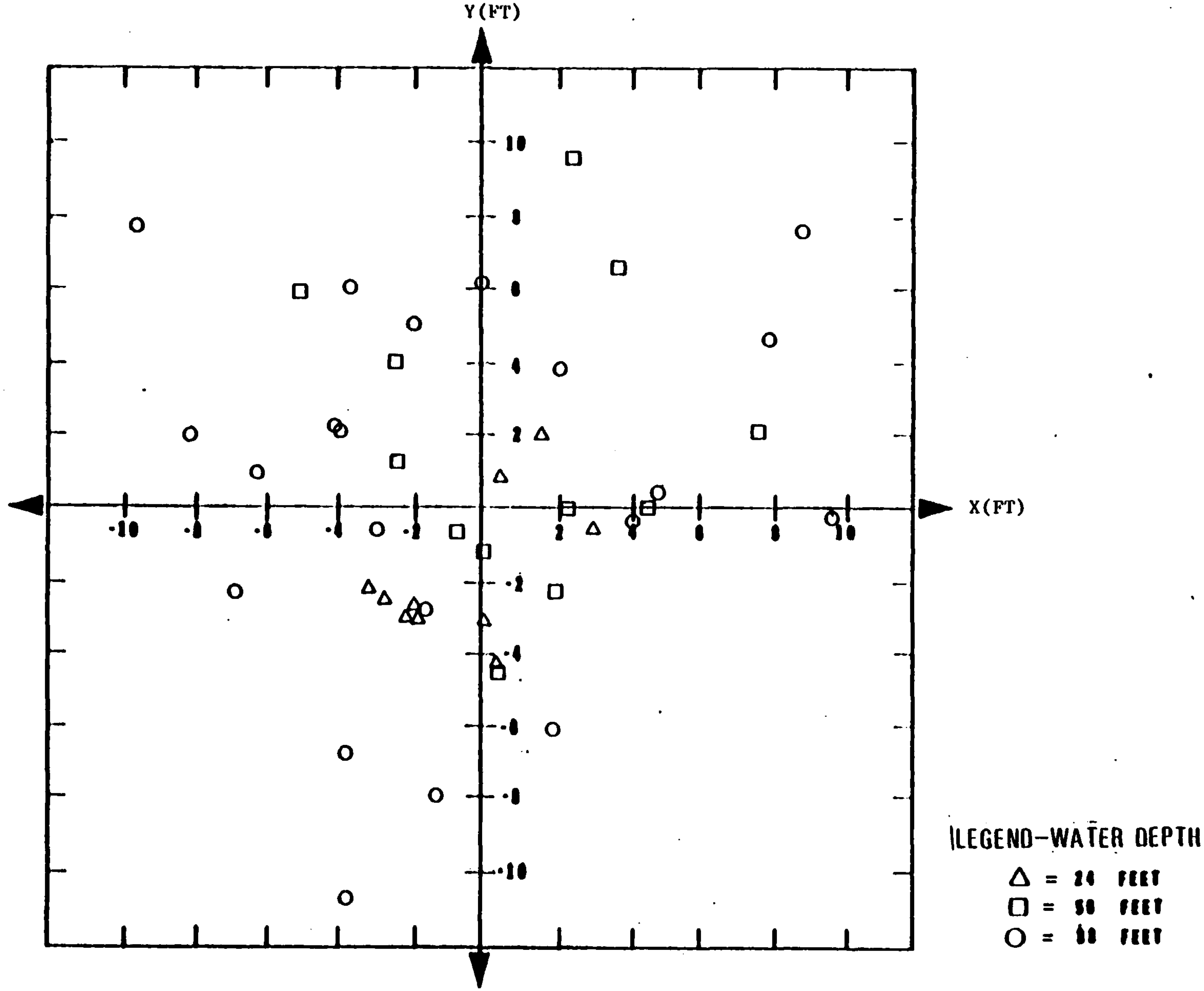


FIGURE 3-8 PORT HUENEME (CEL) SINKER OFFSETS FOR 8500 LB SINKERS

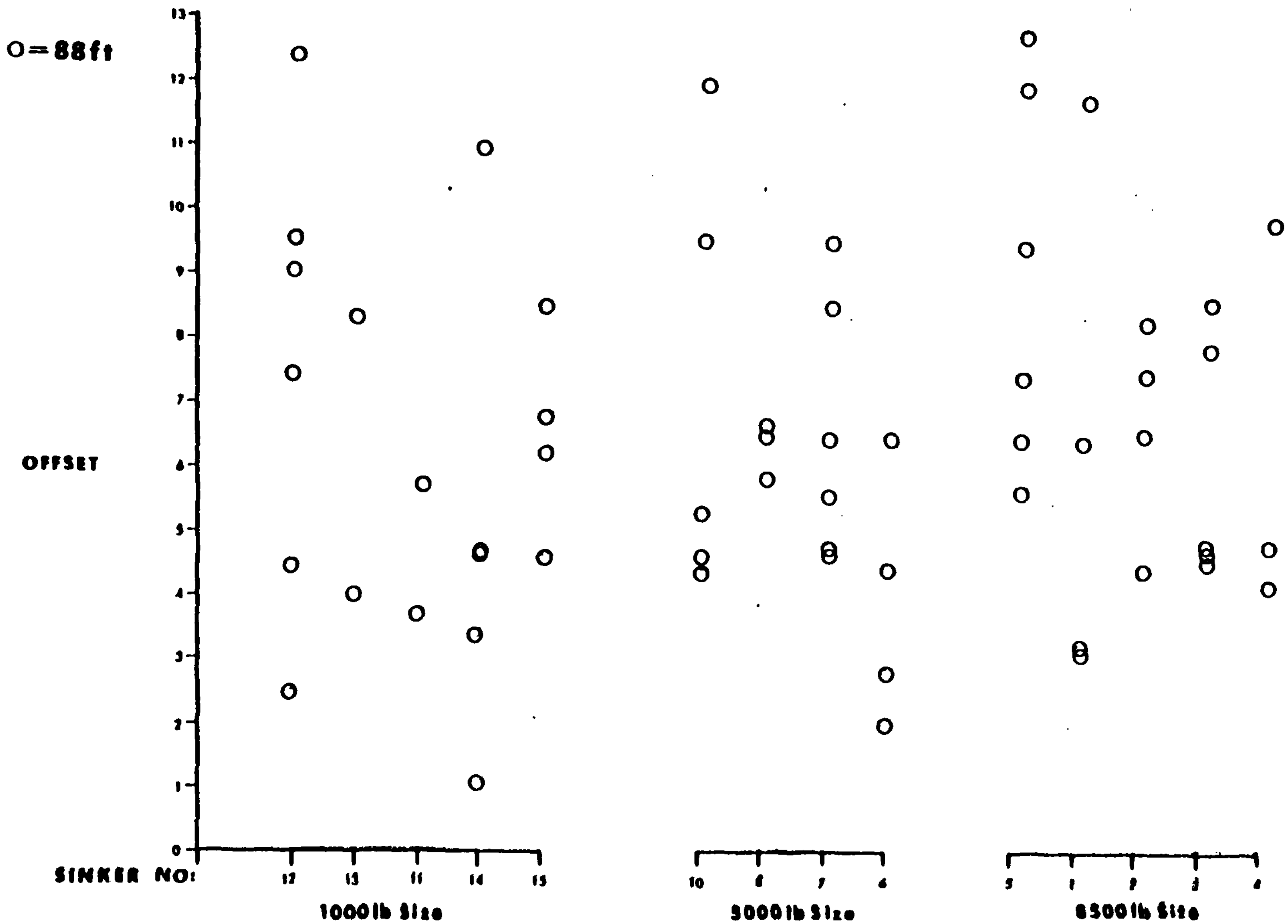


FIGURE 3-9 CEL PORT HUENEME SINKER DROPS FOR EACH INDIVIDUAL SINKER IN 88 FEET OF WATER

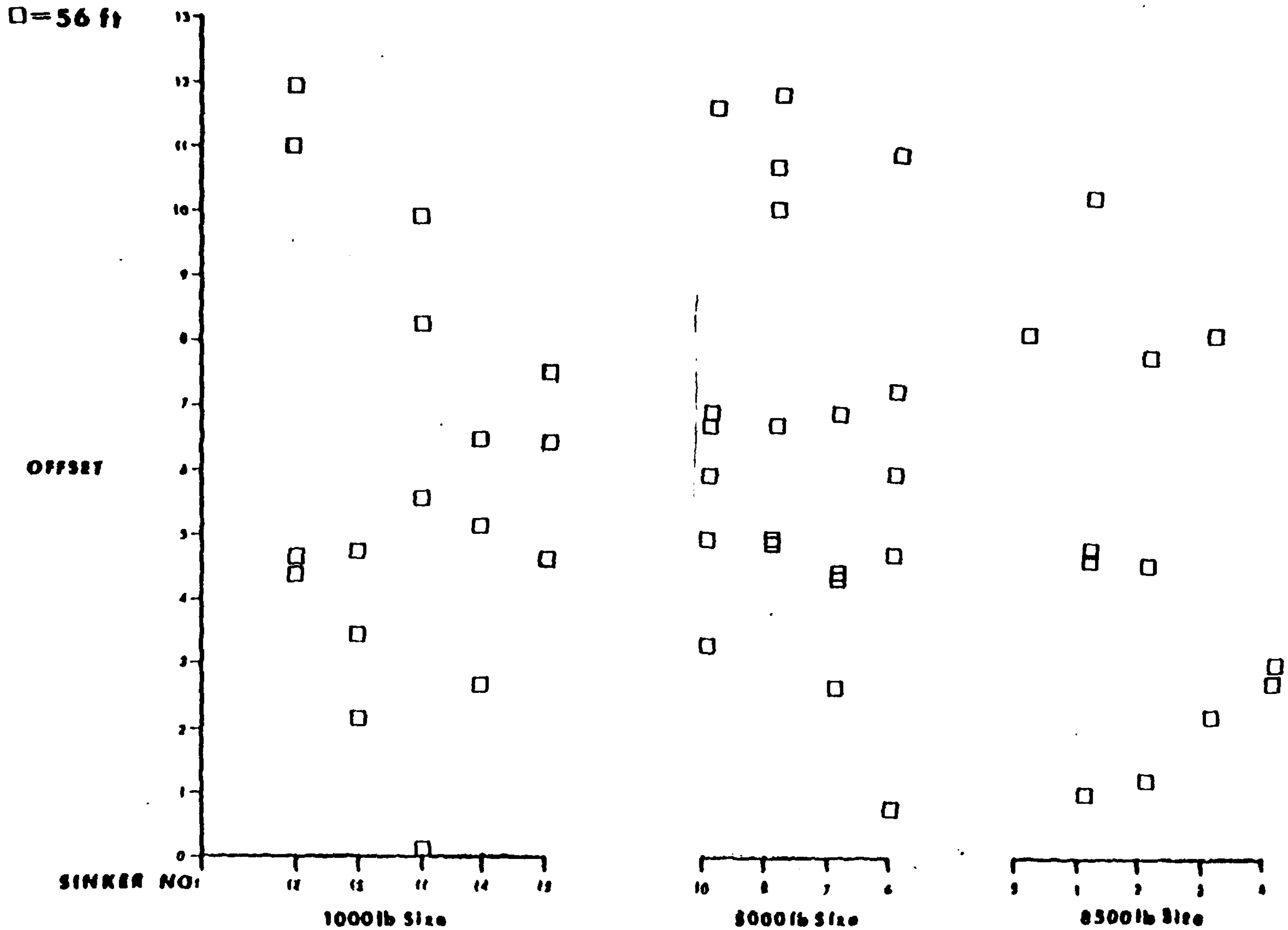


FIGURE 3-10 CEL PORT HUENEME SINKER DROPS FOR EACH INDIVIDUAL SINKER IN 56 FEET OF WATER

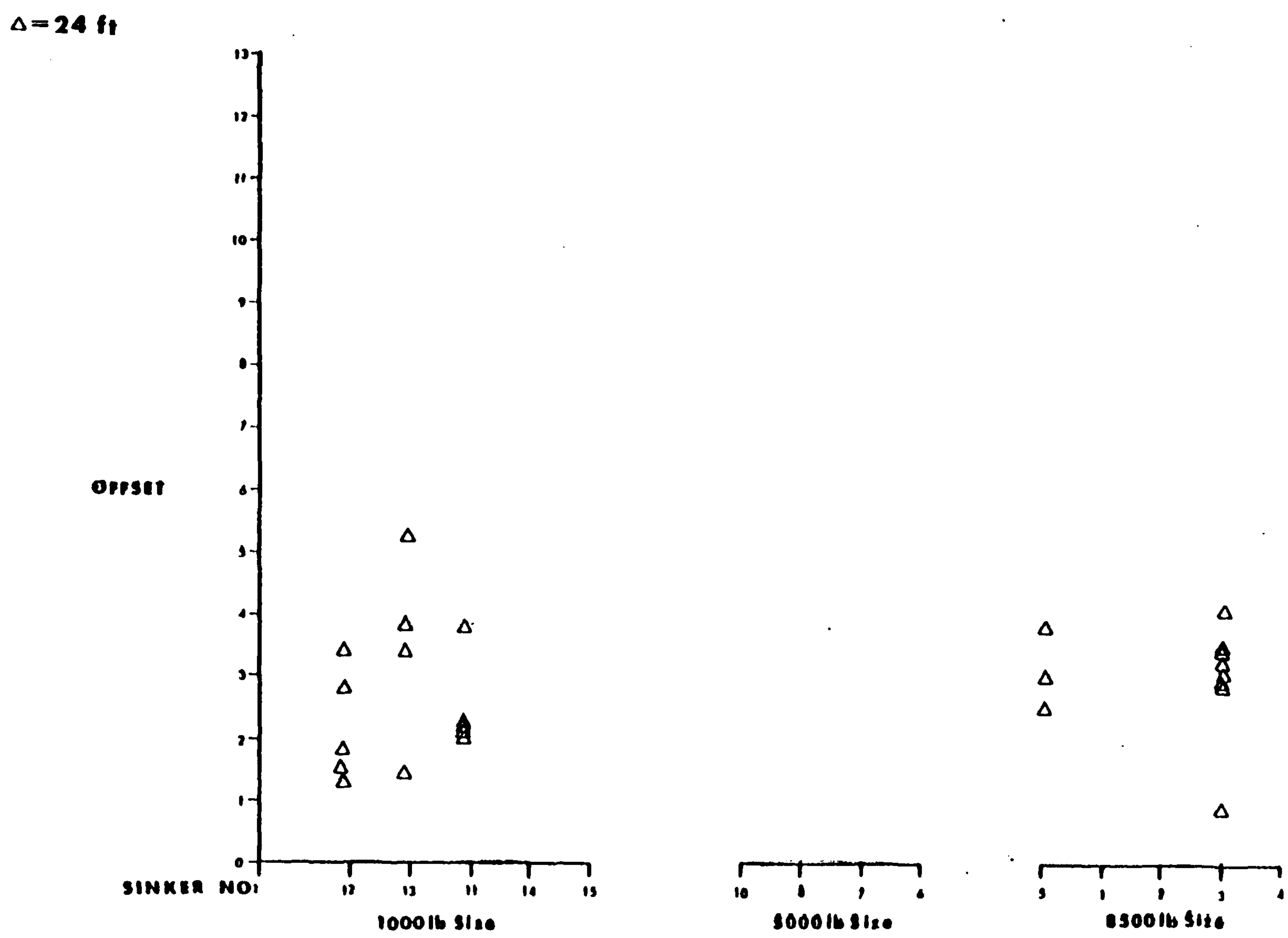


FIGURE 3-11 CEL PORT HUENEME SINKER DROPS FOR EACH INDIVIDUAL SINKER IN 24 FEET OF WATER

where μ_x and μ_y are the means of the x and y data, σ_x and σ_y are the standard deviations (s.d.'s) of the x and y data, and R is the correlation coefficient between the x and y data.

2. The standard deviations along the axes are equal, (See Table 3.1), as determined by a standard F-test on the variances of the data.

3. There is no correlation between the data along the two axes: R = 0. The observed coefficients vary between .06 and .25 in absolute value, and are not statistically significant.

Because of 2 and 3 above, the offsets are distributed as a sample of a special case of the bivariate normal density function, called the circular normal:

$$f(x,y) = \frac{1}{2\pi\sigma^2} \exp \frac{(x-\mu_x)^2 + (y-\mu_y)^2}{-2\sigma^2}$$

where $\sigma_x = \sigma_y = \sqrt{\frac{\sum (x - \bar{x})^2}{n-1}} = \sigma.$

The range (offset) density function derived from this circular normal distribution is:

$$f(r) = \frac{1}{\sigma^2}\, r \exp\left(- \frac{r^2}{2\sigma^2}\right)$$

where $r = \sqrt{(x-\mu_x)^2 + (y-\mu_y)^2}$, and σ is the $\sigma = \sigma_x = \sigma_y$ above. Note that this is not a normal distribution. It is in fact a special case of the Weibull distribution, called the Rayleigh distribution. Its mean is $\sigma\sqrt{\pi/2}$, and its variance is $\sigma^2\,(2-\pi/2)$.

Kolmogorov-Smirnov tests on the ranges of the NSWC and CEL data are shown in Figures 3-12a and 3-12b. Here the empirical CDFs (cumulative distribution functions) are fit by the theoretical CDFs. For the data taken as a whole, $\mu_x = \mu_y = 0$; this is not necessarily the case for individual blocks of data, as will be seen in the next section. It is clear that the fits are very good, and the test confirms this. In effect, this "validates" the above three conclusions, and agrees with intuitive expectations.

3.2 Offset Bias and Directionality.

It was expected that the mean of the sinker offsets would be directly underneath the suspended sinker at the origin of the coordinate system (i.e., that $\mu_x = \mu_y = 0$) since there was no current. Similarly, sinkers were not expected to tend to fall in the same direction on each drop relative to either the sinker or to true North. These two properties, called bias and directionality respectively, were tested as null hypotheses, as follows:

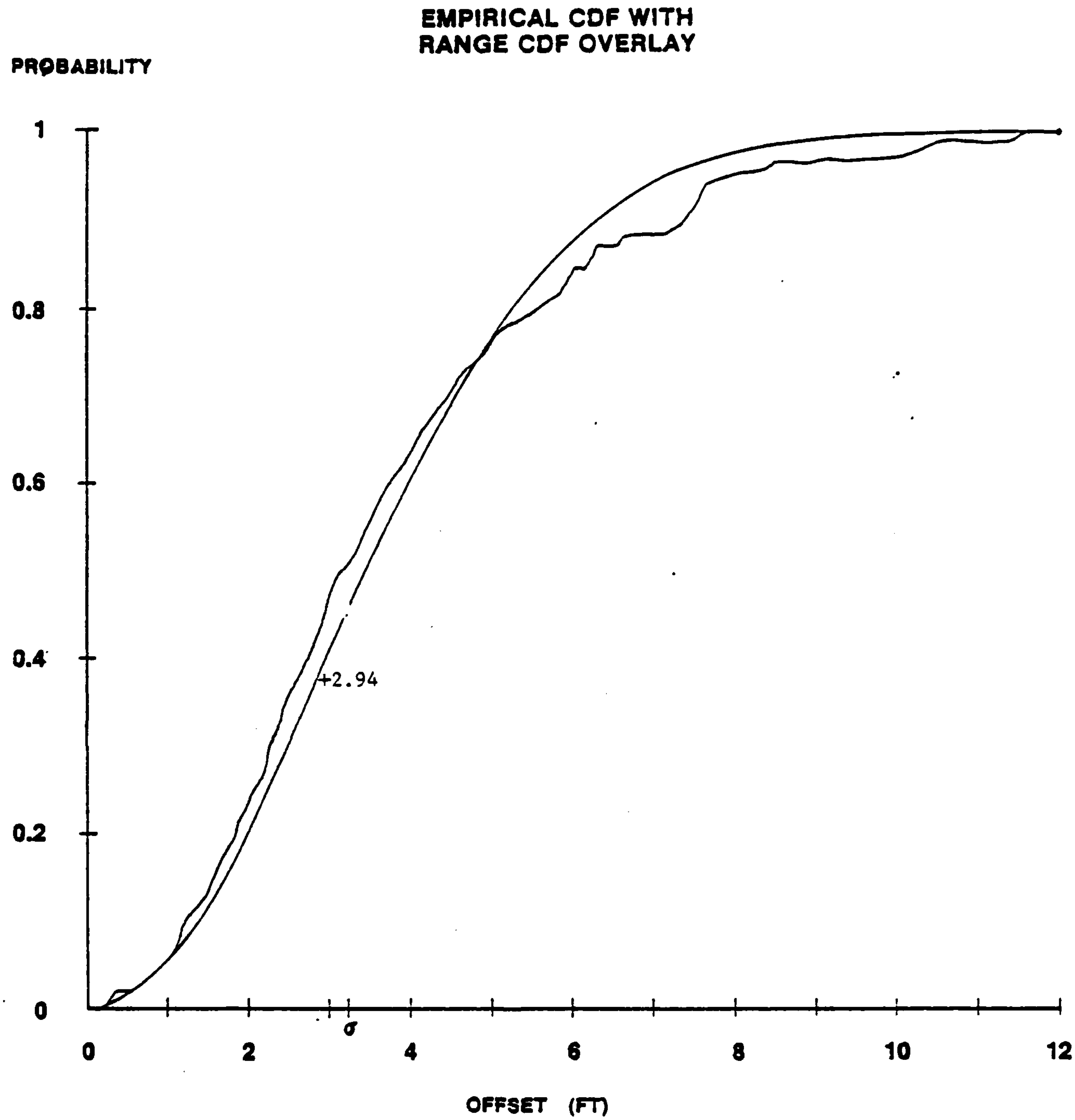


FIGURE 3-12a KOLMOGOROV-SMIRNOV TEST PLOT OF NSWC STILL WATER TANK CUMULATIVE DISTRIBUTION OF OFFSETS WITH A RANGE CDF OVERLAY

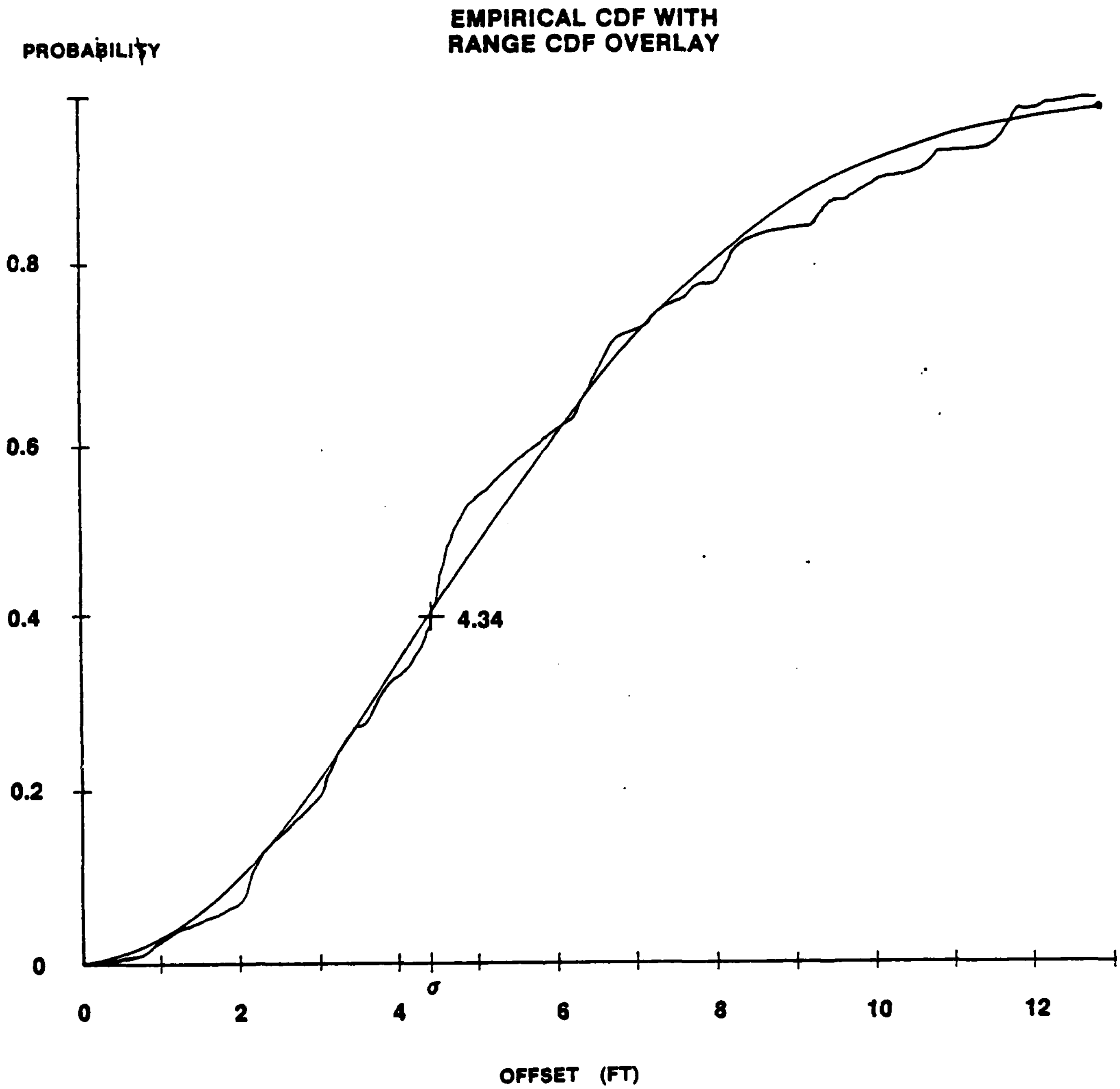


FIGURE 3-12b PORT HUENEME CUMULATIVE DISTRIBUTION OF OFFSETS WITH A RANGE CDF OVERLAY

1st hypothesis: that the mean of the sinker's distribution is at the origin, i.e., the sinker is unbiased. The test was a standard t-test, using the ratio of the range of the sample mean over the sample standard deviation. The figures for the NSWC sinkers, and the CEL 1000-lb. sinkers (which exhibited the only bias of the CEL sinkers) are given in Tables 3-1a and 3-1b. The bias distance is the distance of the mean of the drops from the origin. The bias direction represents the angle of the mean from the reference axis (positive y-axis as shown in Figure 3-18). If a new coordinate system (x', y') is centered at the mean, the Orientation Angle is the angle through which the axes are rotated to minimize the standard deviation in the y' direction.

2nd hypothesis: that the distribution of the drops' offsets is uniform through 360^{o}, i.e., that the sinker is not directional. A Hodges-Ajnes test (Reference 2) was used. This is not a well-known procedure, so a brief description follows.

This test involves the polar plotting of the various offset directions for a group of data listed in Appendix B at a unit distance from the origin. An imaginary line is then drawn between any two adjacent points through the origin and subsequently the number of data points on either side of this line is determined by inspection. This imaginary line is then rotated about the origin until the minimum number of points on either side of this line has been determined. This minimum number is then compared with tabular values based on the total number of data points present to determine whether the hypothesis of uniformity should be rejected or accepted. Scatter plots (Figures 3-13 through 3-17) are used to demonstrate this test on the NSWC sinkers, using direction relative to the sinker, not the tank. The 0^{o} reference is taken to be the direction from the centroid to the center of gravity, for reasons explained in the next section.

The results of the two tests agree fairly well. In general, it seems the bias test is at a higher level (i.e., more likely to be rejected).

NSWC: All five sinkers are biased. #2 and #6 are not directional at the 95% level, but both sinkers are directional at the 90% level. This is true with directions taken relative to the sinker; with directions relative to the tank, no bias or directionality is found.

CEL: The 1000 lb. sinkers, tested block by block, are biased. No other significant bias was found, although a fairly large number of individual blocks reach the 95% level. No directionality was found. Directions were not recorded relative to the sinkers, therefore only compass directions were used in the CEL test. The slight bias at CEL may be due to a small current, or some other small systematic error. It has a 10-15% probability of occurring by chance.

TABLE 3-1a. TABLE OF BIAS DISTANCES, DIRECTIONS, MAJOR AND MINOR STANDARD DEVIATIONS AND ORIENTATION ANGLES FOR SINKERS DROPPED AT NSWC

SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (feet)	BIAS DISTANCE (feet)	BIAS DIRECTION (degrees)	σ_x (feet)	σ_y (feet)	ORIENTATION ANGLE (degrees)	NUMBER OF POINTS	T-TEST SIGNIFICANCE LEVEL†
250	4	24	1.47	-106.4	0.74	0.61	70	10	**
		56	3.42	-157.1	0.69	0.01	90	4	**
		88	3.34	-101.9	3.50	2.05	65	10	**
500	1	40	1.41	-35.4	2.08	0.35	20	3	--
		56	3.29	-26.0	3.15	0.61	45	4	*
		72	2.40	-104.9	3.33	1.83	40	3	--
		102	6.15	-49.5	3.77	0.03	70	2	*
500	2	56	1.34	-44.7	1.51	1.11	20	12	**
		72	2.02	21.1	0.46	0.01	20	2	*
		102	0.63	20.7	4.22	0.49	75	3	--
500	6	24	0.58	-128.6	0.68	0.00	20	4	--
		40	1.37	43.2	3.16	1.56	60	4	--
		56	1.54	82.2	2.36	1.16	40	26	**
		72	1.66	86.3	2.76	1.90	05	4	--
		88	4.94	15.0	1.79	0.00	75	4	**
1000	5	24	2.04	5.4	1.82	0.41	75	10	**
		40	3.04	2.1	2.08	0.69	55	8	**
		56	5.52	-14.3	1.49	1.08	85	16	**
		72	5.70	6.6	4.18	1.86	65	8	**
		88	5.31	4.5	7.79	4.01	20	10	*

Orientation Angle calculated to the nearest 5°

† ** Indicates 99% significance level
* Indicates 95% significance level

All five sinkers are biased as 95% level.

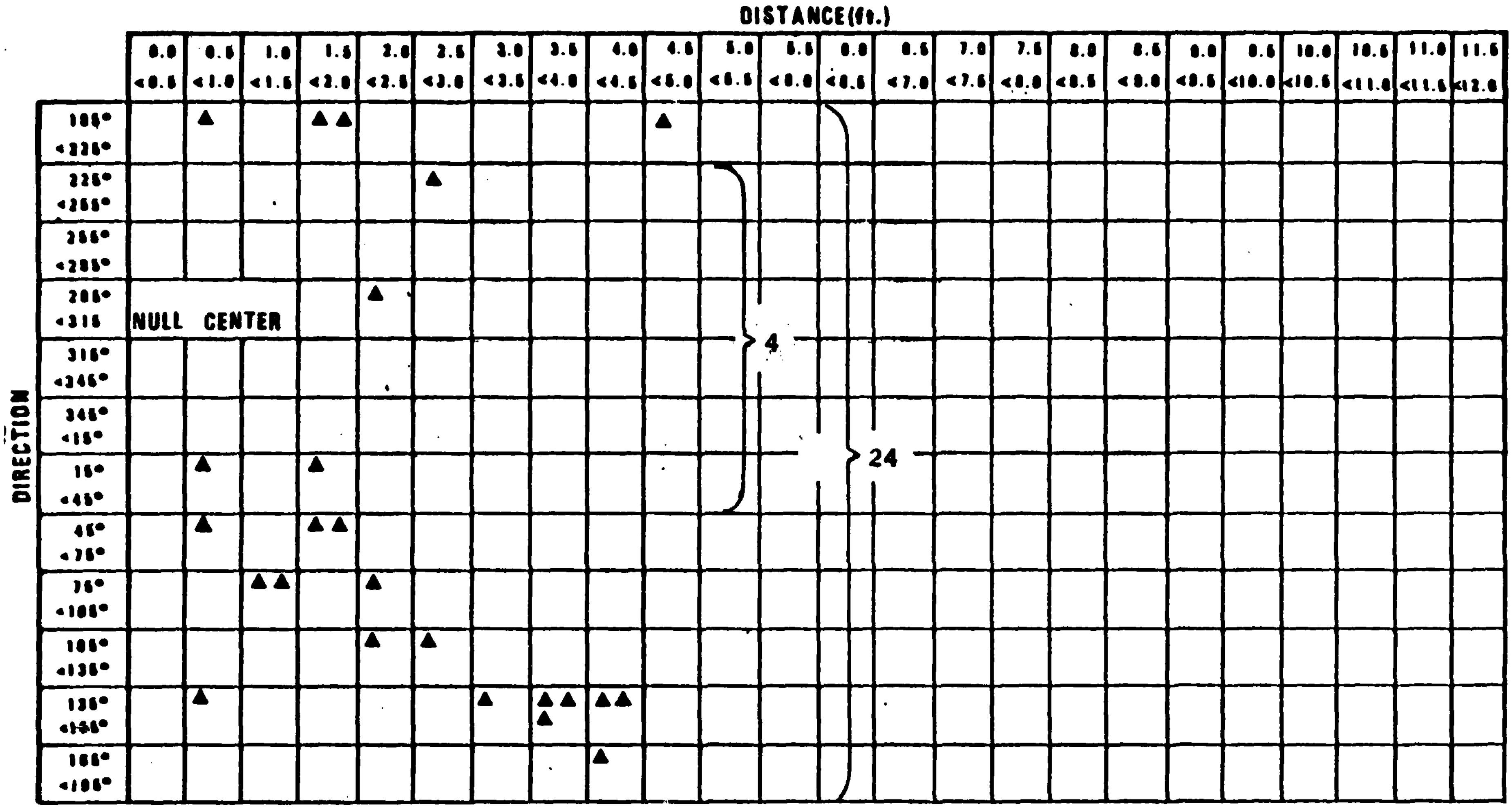
TABLE 3-1b. TABLE OF BIAS DISTANCES, DIRECTIONS, MAJOR AND MINOR STANDARD DEVIATIONS AND ORIENTATION ANGLES FOR THE 1000-POUND SINKERS DROPPED AT CEL

SINKER SIZE (lbs)	DROP HEIGHT (feet)	WATER DEPTH (feet)	BIAS DISTANCE (feet)	BIAS DIRECTION (degrees)	σ_x' (feet)	σ_y' (feet)	ORIENTATION ANGLE (degrees)	NUMBER OF POINTS	t TEST SIGNIFICANCE LEVEL†
1000	0	24	1.14	-52.1	2.21	1.02	30	5	90%
	4	24	1.04	-35.1	2.90	1.17	25	10	90%
	0	56	3.50	-73.4	5.80	3.25	65	6	90%
	4	56	2.25	-30.5	6.34	3.27	20	5	--
	6	56	0.50	155.8	5.61	2.62	35	6	--
	0	88	5.50	11.3	3.33	1.07	35	6	**
	4	88	1.45	-98.4	5.11	4.28	50	9	--
	6	88	4.45	-35.6	4.80	4.13	45	6	*

Orientation Angle calculated to the nearest 5°

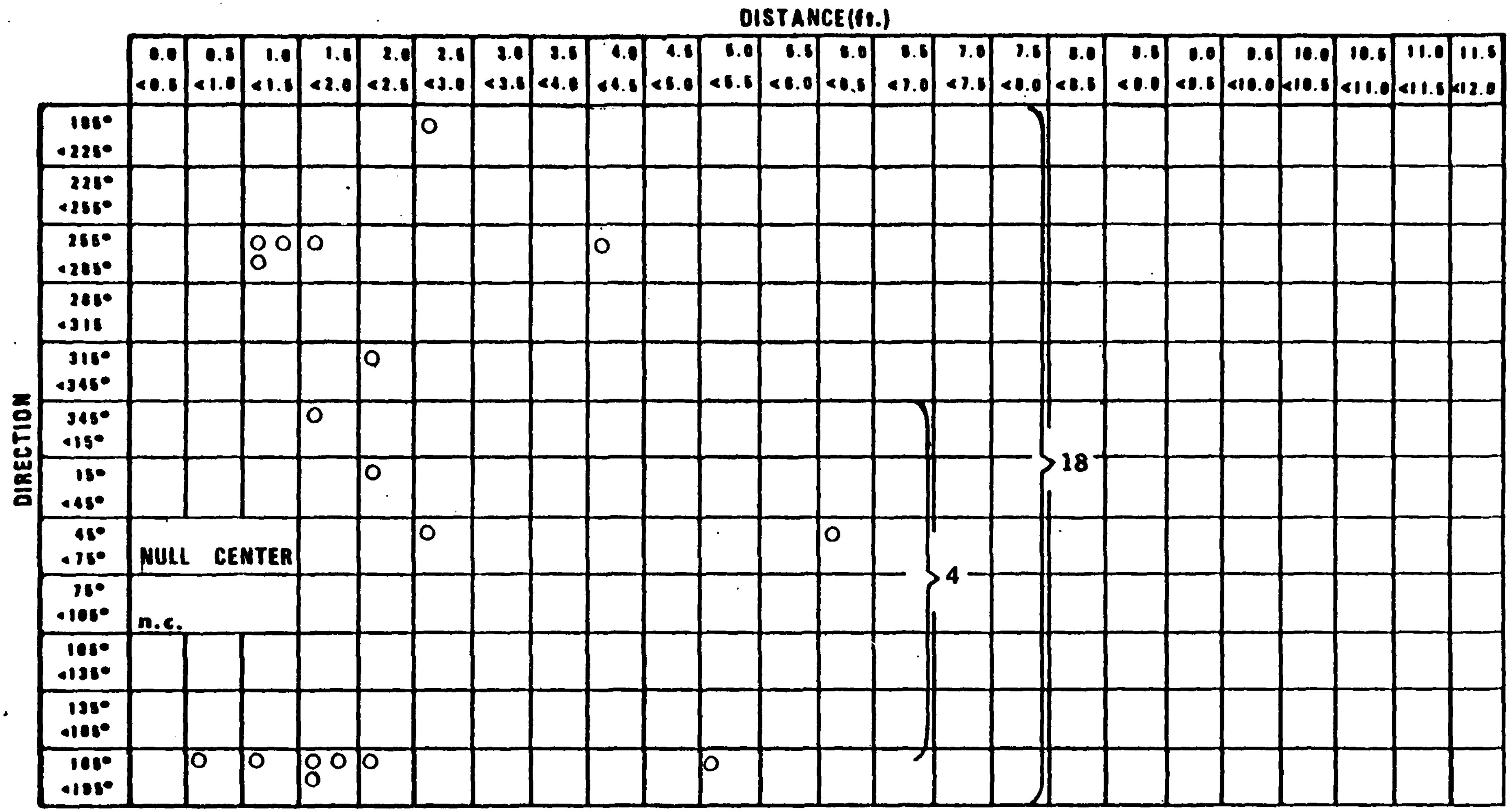
† ** indicates 99% significance level
* indicates 95% significance level

Although generally tests were not made for 90% significance, note that first three reach that level. Taking this into consideration, the sinker indicates bias at about 95% level.



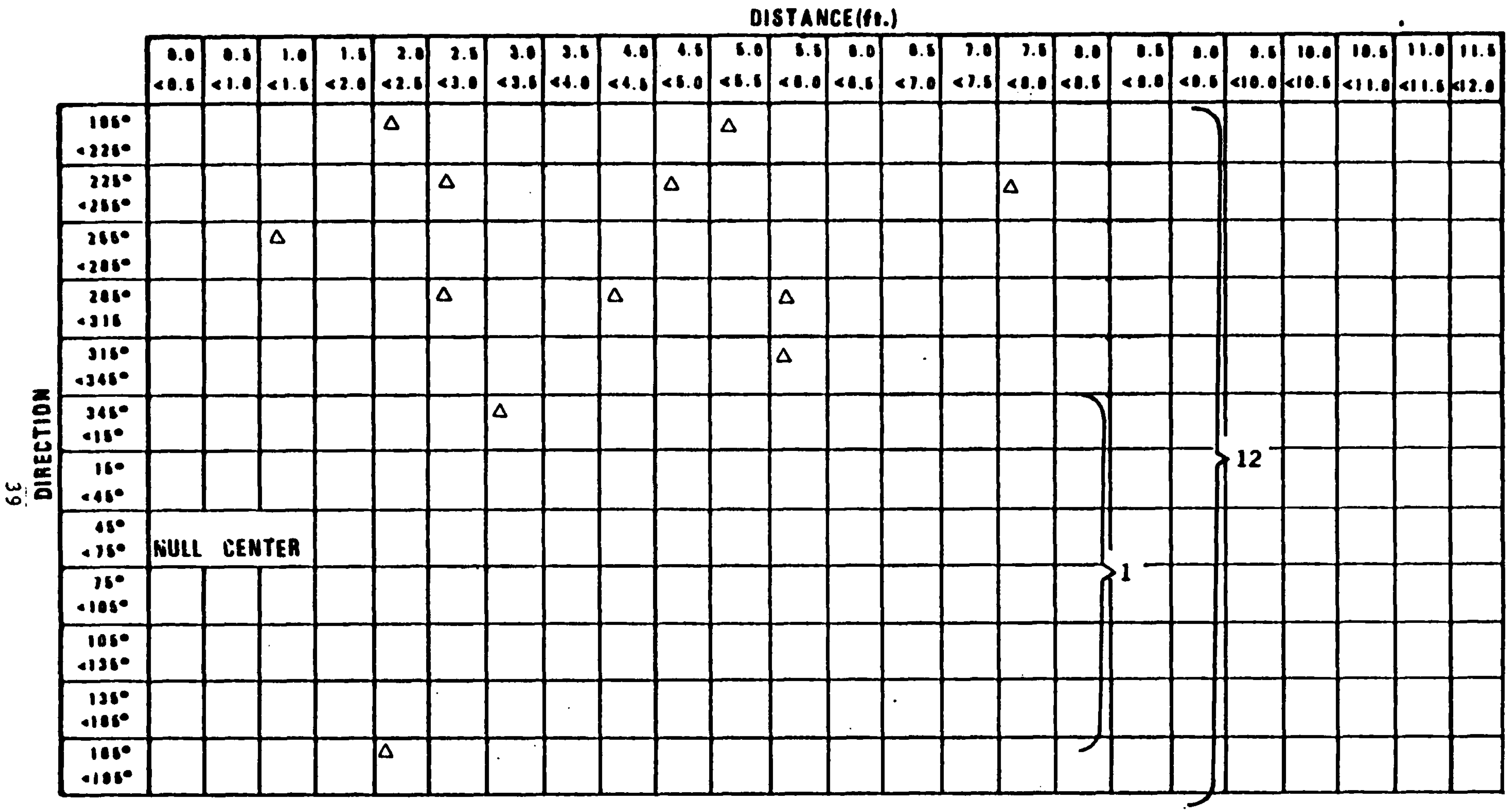
4/24 DIRECTIONAL AT 95% CONFIDENCE LEVEL ACCORDING TO HODGES-AJNES TEST

FIGURE 3-13 SCATTER DIAGRAM (c.g.) OF NSWC DATA FOR SINKER #4 (250LBS)



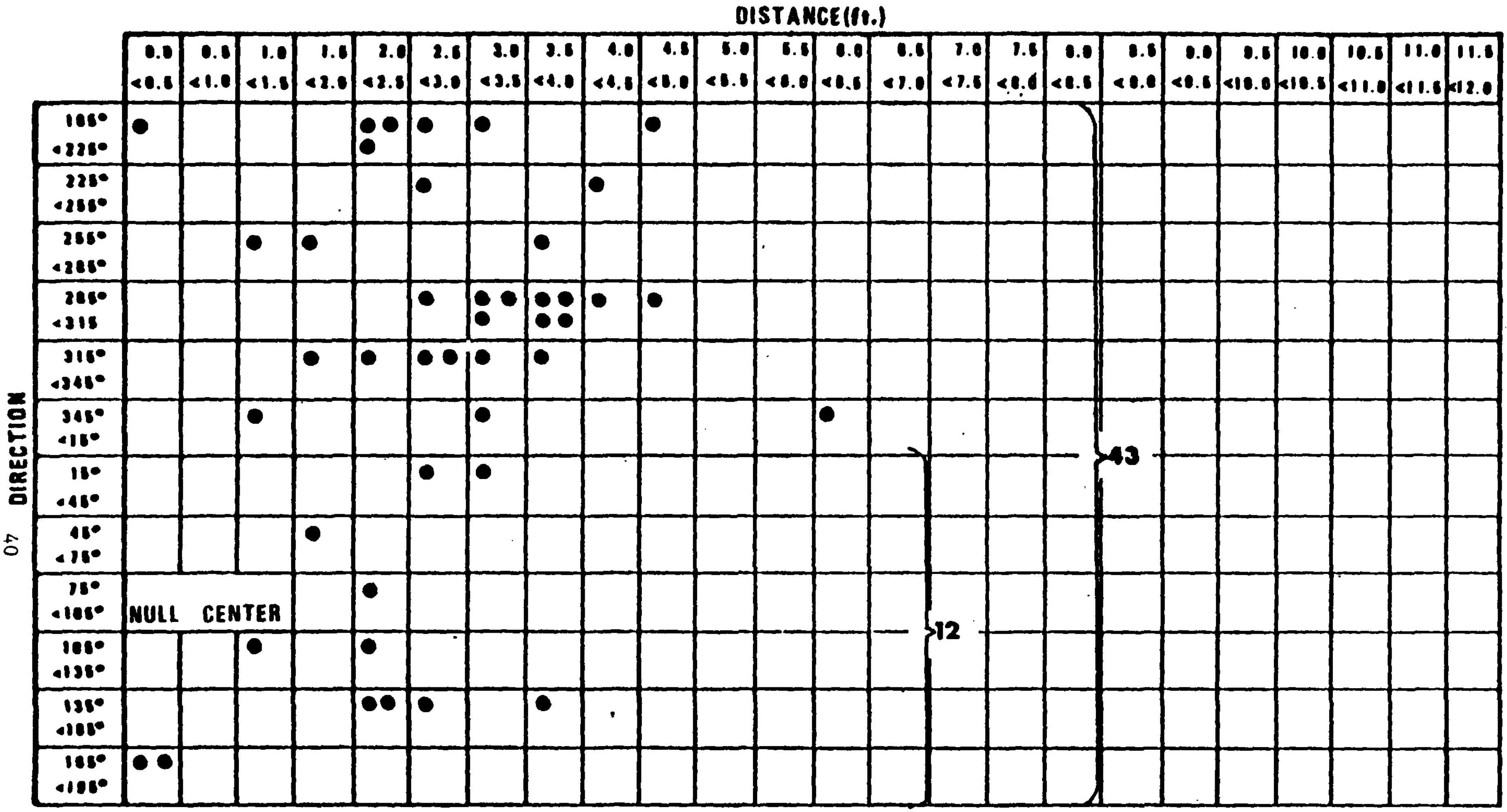
4/18 : DIRECTIONAL AT 95% CONFIDENCE LEVEL ACCORDING TO HODGES - AJNES TEST

FIGURE 3-14 SCATTER DIAGRAM (c.g.)OF NSWC DATA FOR SINKER #1 (500LBS)



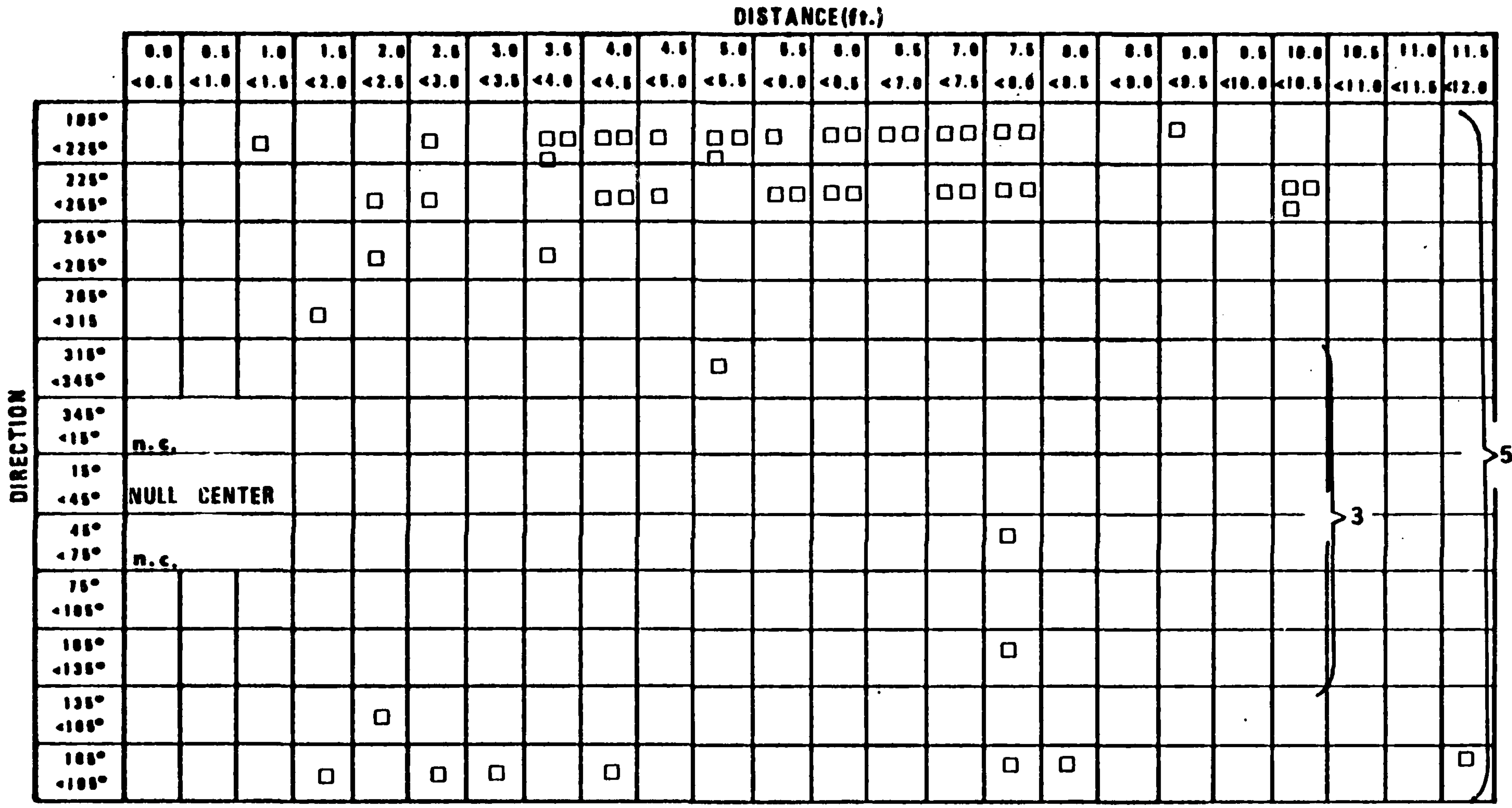
1/12 : DIRECTIONAL AT 90% CONFIDENCE LEVEL ACCORDING TO HODGES-AJNES TEST

FIGURE 3-15 SCATTER DIAGRAM (c.g.) OF NSWC DATA FOR SINKER #2 (500LBS)



12/43: DIRECTIONAL AT 95% CONFIDENCE ACCORDING TO HODGES-AJNES TEST

FIGURE 3-16 SCATTER DIAGRAM (e.g) OF NSWC DATA FOR SINKER #6 (500LBS)



3/51 : DIRECTIONAL AT 95% CONFIDENCE LEVEL ACCORDING TO HODGES-AJNES TEST

FIGURE 3-17 SCATTER DIAGRAM (c.g.) OF NSWC DATA FOR SINKER #5 (1000 LBS)

3.2.1 Offset Bias and Directionality Correlation

No explanation was found for the definite directionality of the NSWC sinkers. It was postulated that some correlation might be found between the directionality and the center of gravity offset direction. The locations of the centers of gravity of the sinker with respect to their centroids, as shown in Figure 3-18 were compared to the offset directions. The results of this comparison are shown in the scatter diagrams for each NSWC sinker, Figures 3-13 through 3-17. 0° represents the direction from the centroid to the center of gravity. The smaller bracket indicates the least number of drops occuring within any given interval of 180° (the "null side") while the total number of drops is shown next to the larger bracket. The midpoint of the null side is indicated as the "null center". 180° from the null center is considered the preferred direction for the data presented. Where there is latitude in selecting the null side interval, secondary null centers are indicated as "(n.c.)". Similarly Figure 3-19 presents data for all NSWC sinker offsets relative to the diagonal line drawn from the centroid to the corner nearest the center of gravity.

The preferred direction of the offsets shows no correlation with the center of gravity. It must be noted that the center of gravity is displaced a relatively small amount from the centroid in all the NSWC sinkers. The angular acceleration due to this moment is considered in more detail in section 4.2.2. Nevertheless, it seems intuitively reasonable that the center of gravity displacement may be significant, and it is felt that any future work should take this into consideration.

3.3 Factor Effects and 95% Confidence Circles

Since the distributions are circular normal the confidence ellipses are actually circles. These distributions are composed of the convoluted effects of (1) the population of individual sinker biases discussed above and (2) the variability about the biases. Since no information has been collected on the population of actual sinkers used by the Coast Guard, the contributions of (1) are unknown values. (This postulation emerged from an attempt to explain the biases found in the data). Without this information only the variability about the bias, (2), can be inferred from this data.

As a means of expediency in the analysis of the data, the following approximations were made:

a. The finite size of the data sample is assumed to be sufficiently large enough that bivariate normal statistics are used vice the appropriate F-distribution which actually applies.
b. The deviation about the origin is used vice the standard deviation about the sample mean.

The errors of these two approximations are small and can reasonably be expected to tend to cancel one another. Thus the formula for the "standard" deviation is:

$$\sigma = \sqrt{\frac{\Sigma(x^2 + y^2)}{2n}}$$

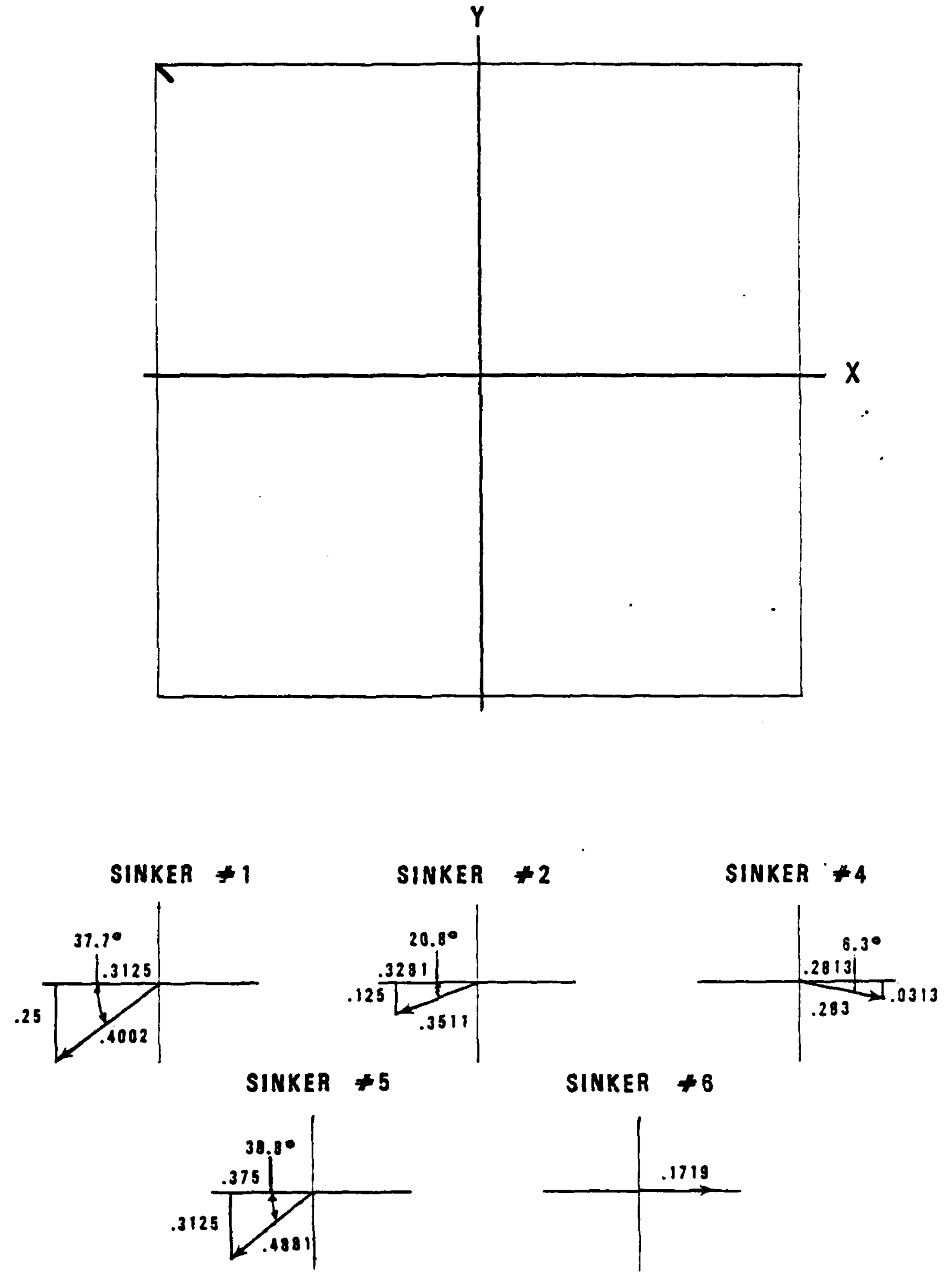


FIGURE 3-18. LOCATIONS OF CENTER OF GRAVITY OF SINKERS

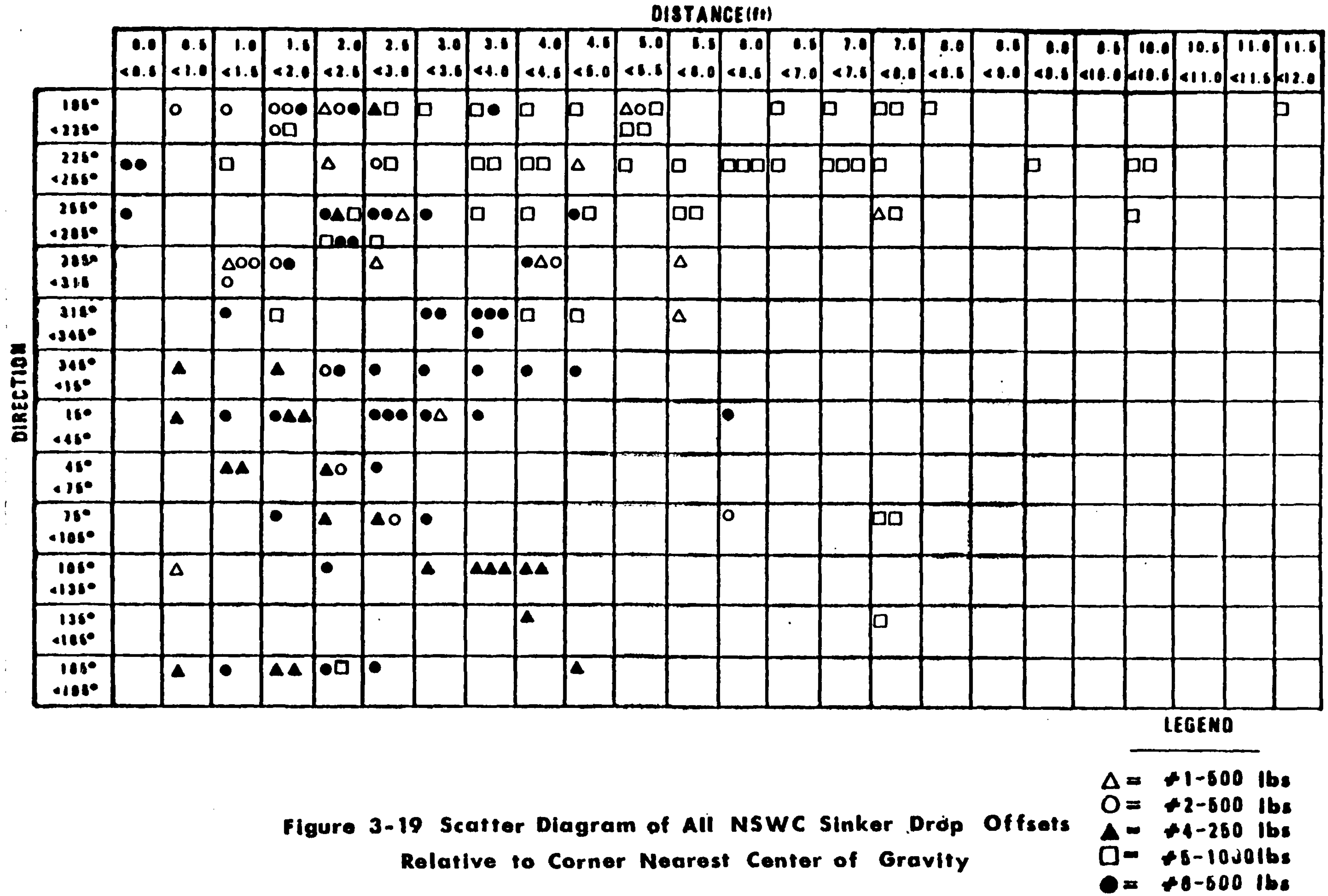


Figure 3-19 Scatter Diagram of All NSWC Sinker Drop Offsets Relative to Corner Nearest Center of Gravity

The pooled (average) x and y variance is used, with 0 for each mean, and the divisor is n, since no degree of freedom is lost in the calculation of the mean.The radius of the 95% confidence circle is 2.45 timesσ, and the radius of the 90% circle is 2.15 timesσ, according to well-known bivariate normal theory.

Sinker size, water depth, and drop height were the main factors investigated. Two methods were used to determine factor effects: analysis of variance and factorial analysis. Regression equations were used to express the radii of the confidence circles as functions of the factors. All such analyses were based on the circular normal σ's.

It should be made clear that the confidence circle obtained in this fashion may not entirely encompass the one obtained in the usual way, centered around the sample mean. This will happen not when the bias is too large, as might be expected, but rather when it is too small: that is, when the sinker is unbiased. The 95% confidence circle about the assumed mean (0,0) has as its radius 2.45 times the circular normal σ, where σ is computed using n degrees of freedom. The 95% confidence circle about the sample mean (x, y) has as its radius 2.45 times the sample standard deviation s.d., where s.d. is computed with n-1 degrees of freedom. Thus when the sinker is unbiased, the centers of the two circles coincide, but the radius of the "sample" confidence circle is slightly larger. (The numerators of σ and s.d. are the same, but the denominators are n and n-1, respectively). In addition, use of the F-Distribution for the sample size of the data will yield a factor larger than 2.45 for the 95% confidence circle.

. Because of considerable differences between the two groups of data, NSWC and CEL, they are considered separately.

3.3.1 NSWC Factor Effects and Confidence Circles

Table 3.2 contains all the circular normalσ^2's for the sinkers at NSWC. The most important part of this experiment is Test Series A. Test series A consisted of a complete 2^3 factorial design experiment, with five drops in each cell. The factors and their levels were:

Sinker size (Ss):	250 & 1000 lbs
Water depth (Wd):	24 & 88 feet
Drop height (Ht):	0 & 6 feet

The effect of the presence or absence of chain attached to the sinker (as described in Section 2) was also tested, using a blocked experimental design. As explained above, the test was an ANOVA done on the actual offsets. The results are given in Figure 3-21, as an illustration of this procedure. An ANOVA using the circular normalσ's produced the same effects except of course for the one concerning chain, which it was not capable of determining because the effect is confounded with the triple cross product, which is used to estimate error in this procedure.

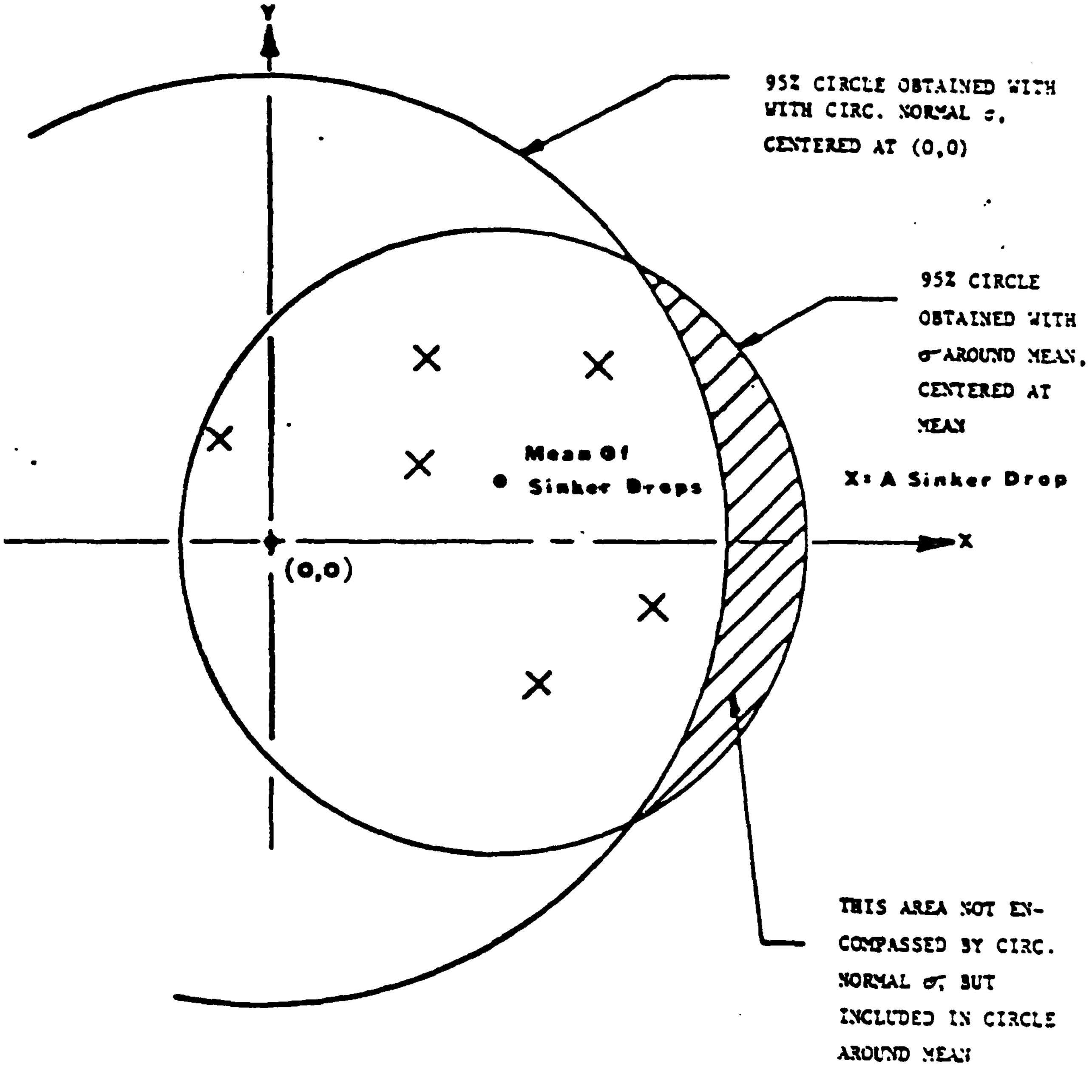
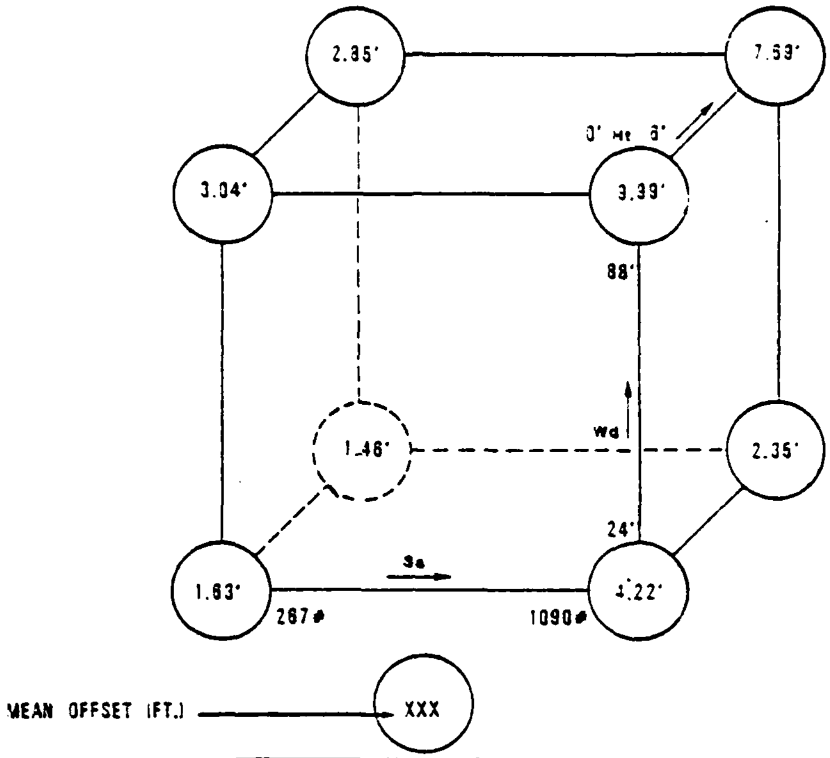


FIGURE 3-20: CONFIDENCE CIRCLE COMPARISON



POOLED STANDARD DEVIATION (FT)	=	.48
POOLED VARIANCE (FT)^2	=	.23
NUMBER OF DEGREES OF FREEDOM	=	32
STUDENT T DISTRIBUTION VALUE	=	2.04
CONFIDENCE LEVEL	=	95%
MINIMUM SIGNIFICANT FACTOR EFFECT	=	.69

FACTOR EFFECTS	
Mean	+4.15
Sa	+3.32
Wd	+3.48
Ht	−1.13
SaWd	+2.08
SaHt	−0.95
WdHt	−0.11
SaWdHt	−0.10

COEFFICIENTS OF REGRESSION EQUATION	Coded	Decoded
A_0	+ 4.15	$+ 7.31 \times 10^{-1}$
A_1	+ 1.91	$+ 1.60 \times 10^{-2}$
A_2	+ 1.74	$- 7.01 \times 10^{-3}$
A_3	− 0.57	$+ 5.65 \times 10^{-4}$
A_4	+ 1.04	$+ 9.29 \times 10^{-5}$
A_5	− 0.48	$- 3.13 \times 10^{-4}$
A_6	− 0.06	$+ 2.94 \times 10^{-5}$
A_7	− 0.05	$- 1.30 \times 10^{-6}$

$$\text{OFFSET} = A_0 + A_1\,Sa + A_2\,Wd + A_3\,Ht + A_4\,Sa\,Wd + A_5\,Sa\,Ht + A_6\,Wd\,Ht + A_7\,SaWdHt$$

FIGURE 3-21
FACTORIAL DIAGRAM FOR THE MOST PROBABLE OFFSET
(IN FEET, DEVELOPED FROM TEST SERIES A, NSWC)

TABLE 3-2. CIRCULAR NORMAL σ^2 FOR NSWC SINKER DROPS

SINKER		#4 (250 lbs)		#1 (500 lbs)		#2 (500 lbs)		#6 (500 lbs)		#5 (1000 lbs)	
WATER DEPTH (ft)	DROP HEIGHT (ft)	CIRCULAR NORMAL σ^2	n	CIRCULAR NORMAL σ^2	n	CIRCULAR NORMAL σ^2	n	CIRCULAR NORMAL σ^2	n	CIRCULAR NORMAL σ^2	n
24	0	1.45	5					0.42	2	9.02	5
	6	1.26	5					0.63	2	2.90	5
	T	1.36	10					0.53	4	5.96	10
56	0	7.85	2			5.6	4	5.46	6	10.79	2
	1.5			12.60	1	3.61	1	6.12	2	17.34	4
	3			10.40	1	3.48	3	4.55	10	16.81	4
	4.5			7.09	2	0.66	1	5.6	1	14.73	4
	6	3.56	2			2.34	3	1.12	7	12.3	2
	T	5.7	4	9.30	4	3.68	12	3.76	26	15.11	16
88	0	5.60	5					11.18	2	50.76	5
	6	4.79	5					4.37	2	30.12	5
	T	5.20	10					7.78	4	40.44	10
40	1.5							5.6	4	6.94	4
	4.5			2.48	3	0.19	1			5.93	4
	T			2.48	3	0.19	1	5.6	4	6.44	8
72	1.5			3.76	2	1.74	2			28.97	4
	4.5			15.57	1			5.60	4	23.84	4
	T			7.70	3	1.74	2	5.60	4	26.41	8
102	3			22.5	2	6.21	3	11.81	1		
56 (dropped on side)	3			27.83	2	25.15	2	25.05	2		

n = number of data points
T row: average σ^2 for all drops in one block

The factor effects were:

1. Offset increases as the following increase: Ss, Wd, Ss x Wd.

2. Offset decreases slightly but significantly as the following increase: Ht, Ss x Ht.

3. The presence or absence of chain, and the cross product Wd x Ht, had no effect.

Therefore, chain was not used in later NSWC drops.

In the later drops, three 500 lb. sinkers were used (as well as the original two sinkers). All five were dropped at various depths and heights between the original ones, namely: Wd: 24', 40', 56', 88'; Ht: 0, 1.5', 3', 4.5', 6'. Also, six drops were made at Wd = 102'. Unfortunately, it was later found that the three 500 lb sinkers had significant differences, and had to be analyzed separately. Since they were used randomly when the design called for a 500 lb sinker, when separated they did not constitute good experimental designs. ANOVA's could not be used in these cases, so regression analysis was substituted. It yielded the following results:

1. Later data does not contradict the test series A results and may be considered to validate the main factor effects obtained there. Specifically, offset increases as Ss and Wd increase, and to a lesser extent, as Ht decreases. The 500 lb sinkers had offsets only marginally greater than the original 250 lb sinker, however. The positive effect of depth was established at 102 feet (test series E).

2. Dropping the sinker on its side approximately doubled the offset (test series F).

3. A small tilt to the sinker prior to release had no effect (test series C).

A regression equation from the test series A factorial experiment, and separate equations for each sinker, are given in Table 3-3. All equations were based on those for the circular normal σ's which are included in the table for completeness. The equations express the radii of the 95% confidence circles as functions of Ss, Wd and Ht. The equations for test series A (which involved sinkers 4 and 5) and the separate equations for #4 and #5, all have good fits as indicated by high R^2 values (R is the correlation coefficient, thus $R^2 = 1$ is a perfect fit). However, all the 500 lb sinker equations have poor fits. This data was not as regular as the data for the 250 and 1000 lb sinkers, and it is felt that further analysis would be fruitless. There is a strong indication that the determination of the relationship would require more experimentation. Also, the idea that the offset depends simply on the sinker weight, even in a nonlinear fashion, is an oversimplification. This is clear because two of the 500 lb sinkers' mean offsets are not significantly larger than that of the 250 lb sinker, while the third 500 lb sinker has a mean offset significantly greater than any of these. Therefore the regression equation from test series A, which attempts

TABLE 3-3. REGRESSION EQUATIONS FOR RADII OF 95% CONFIDENCE CIRCLES AND ONE STANDARD DEVIATION

TEST	AVERAGE RADIUS OF 95% CIRCLE (ft)	REGRESSION EQUATION FOR 95% CONFIDENCE CIRCLE RADIUS AND ONE STANDARD DEVIATION (ft)	R^2
NSWC			
TEST SERIES A #4 & #5	7.40	$r_{95} = 0.22 + 0.1Wd - 0.32Ht + 0.01Ss$	.85
		$r_\sigma = 0.09 + 0.04Wd - 0.13Ht + .003Ss$	
#4 (250 lbs)	4.46	$r_{95} = 2.38 + 0.04Wd - 0.1Ht$	.786
		$r_\sigma = 0.97 + .017Wd - .042Ht$	
#1 -(500 lbs)	6.03		
#2 -(500 lbs)	4.48		
#6 -(500 lbs)	4.83	$r_{95} = 4.88 + 0.02Wd - 0.38Ht$	.205
		$r_\sigma = 1.99 + .008Wd - .157Ht$	
#5 (1000 lbs)	9.90	$r_{95} = 6.67 + 0.08Wd - 0.44Ht$	.932
		$r_\sigma = 2.76 + .032Wd - 0.18Ht$	
CEL		For all CEL sinker sizes and drop height	
24'WATER DEPTH		$r_{95} = 5.34$	
		$r_\sigma = 2.18$	
56' & 88' WATER DEPTH		$r_{95} = 11.12$	
		$r_\sigma = 4.54$	
PRELIMINARY PHASE: 88' WATER DEPTH		For 250 lb sinker, 0 drop height	
		$r_{95} = 4.54$	
		$r_\sigma = 1.85$	

r_{95} = radius of 95% confidence circle
r_σ = radius at one standard deviation
Wd = water depth = 24, 56, or 88 ft
Ht = drop height = 0, 1.5, 3, 4.5, or 6 ft
R^2 = correlation coefficient of the regression; good fit for A, #4, #5.
For #1 and #2 data was insufficient to produce meaningful equation
For #4 (250 lbs) and #2 and #6 (500 lbs) the means are not significantly different; but #1 (500 lbs) is significantly greater than any of these three.

to model this relationship as a linear function of sinker size (weight), is considered unreliable. The equations for #4 and #5 are considered to accurately represent 250 and 1000 lb sinkers. In the 500 lb sinkers, #6 is the most reliable, since considerably more drops were made with this than with the other 500 lb sinkers. In spite of the low R^2 value for this equation, it is the best estimate for 500 lb sinkers that this data provides.

3.3.2 CEL Factor Effects and Confidence Circles

The CEL experiments had basically a 3^3 factorial design, with the following levels:

Sinker size (Ss):	1000, 5000 & 8500 lbs. (five sinkers in each group).
Water depth (Wd):	24, 56, and 88 feet
Drop Height (Ht):	0, 4 and 6 feet

An ANOVA could not be done on all the data at once, since the configuration is not quite a complete 3^3 factorial design. Table 3-4 makes this clear. Therefore, a series of ANOVA's on subsets of the data was done. Only one factor effect was established (at 95% significance) which holds for all levels of the other factors:

A very significant increase in offsets occurs from Wd = 24 feet to the greater depths. Offsets did not increase significantly from Wd = 56 to 88 feet.

The experimental design was set up to detect factor effects for the entire array of different sinker sizes, water depths, and drop heights. Therefore it can be misleading to single out a particular sinker size, for example, and study the data for that group of sinkers separately. In this light, it is interesting to note that there were three significant results for the <u>8500 lb. sinkers only:</u>

1. A very significant increase occurs in offsets as Ht increases.

2. Offsets increase as Wd increases from 56 to 88 feet (as well as from 24 to 56 feet, as with all the CEL sinkers).

3. Considerable variation among individual sinkers exists; this is significant only at the 90% level, however.

Note that the first effect is contrary to that observed at NSWC, where offsets decreased as Ht increased. As pointed out above, an effect of this type cannot be considered truly significant because it was not tested for specifically. However it is included here because it does point out the danger of trying to extrapolate from the NSWC results for smaller sinkers, to gain information about heavier sinkers. Thus it would be dangerous to assume that, based on the NSWC results, offset will always decrease as Ht increases.

TABLE 3-4. CIRCULAR NORMAL σ^2 FOR CEL SINKER DROPS

SINKER		1000 lbs		5000 lbs		8500 lbs	
WATER DEPTH (ft)	DROP HEIGHT (ft)	CIRCULAR NORMAL σ^2	n	CIRCULAR NORMAL σ^2	n	CIRCULAR NORMAL σ^2	n
24	0	3.02	5	-	-	5.57	3
	4	4.95	10	-	-	5.12	6
	6	-	-	-	-	7.68	1
	T	4.3	15			5.51	10
56	0	21.02	6	34.35	8	12.81	6
	4	24.82	5	14.97	8	16.91	6
	6	16.08	6	21.04	6		
	T	20.39	17	23.67	22	14.86	12
88	0	17.04	6	15.63	6	23.98	6
	4	20.46	8	21.43	6	26.45	9
	6	26.53	6	25.66	6	35.13	6
	T	21.26	20	20.91	18	28.22	21

n = number of data points
T row = for all drops in one block

The first two of the above effects are apparent in Table 3-4 and in the ANOVA performed on 8500 lb sinkers for depths of 56 and 88 feet, using either the offsets or the circular normal σ's. Table 3-5 is included as an example of the latter procedure.

Thus there are only two statistically different groups to be considered in the confidence circle determination. The radii of the 95% confidence circles and one standard deviation are:

a. 24 foot depth, all sinkers and drop heights:
   $r_{95} = 5.34'$
   $r_{\sigma} = 2.18'$
b. 56 and 88 foot depths, all sinkers and drop heights:
   $r_{95} = 11.12'$
   $r_{\sigma} = 4.54'$

Unlike the NSWC data, no problems are seen in the interpretation of this data. Particularly since this experiment was conducted under conditions most closely approximating field conditions, it is felt that these figures give the most reliable estimates. They are listed in Table 3-3 also, for the sake of completeness.

3.3.3 Preliminary Phase Results

The preliminary experiment, delineated in Appendix A, was designed to examine the motion of the sinkers during descent, and the effect of current. Almost as a by-product, a statistically significant estimate (i.e., based on a sufficiently large number of drops) of offset for a 250 lb sinker at 88 feet depth was produced. This is given in Table 3-3. It agrees well with the NSWC results.

TABLE 3-5. 2-WAY ANOVA USING CIRCULAR NORMAL σ's: 8500 LB SINKERS VS DEPTHS (56' & 88')

Circular Normal σ's for CEL 8500 lb Sinker

	Sinker Number				
Water Depth (ft)	1	2	3	4	5
56	3.91	3.66	4.16	2.02	4.61
88	4.89	4.74	4.69	4.76	6.47

2-WAY ANOVA

SOURCE	SS	DF	MS	F-STAT	SIG LEVEL
DEPTH	5.17	1	5.17	13.79	**98% (.02)
SINKER SIZE	4.72	4	1.19	3.17	- 88% (.12)
ERROR	1.5	4	.375		
TOTAL	11.39	9			

where:

SS = Sum of Squares
DF = Degrees of Freedom
MS = Mean Square

4.0 HYDRODYNAMIC ANALYSIS AND QUALITATIVE OBSERVATIONS

This section discusses two aspects of the sinker drop which have been lightly treated in the literature of hydrodynamics: the motion of the sinker as it falls, and the effect of current on the offset. In both cases, some observations and/or data were taken, but were insufficient for complete analysis. The hydrodynamic analysis is included for two reasons: to clarify the limited data and observed phenomena by placing them in the context of previous work; and to provide groundwork for possible future research.

4.1 Effect of Current on Offset

As mentioned earlier, it was originally intended to drop the larger size sinkers at Port Hueneme in a 1 kt current, to determine its effect on sinker offset. Unfortunately, no current was present during the test, and so no such data were obtained. The only current data obtained were with small sinkers (500 lbs and less) under controlled conditions at NSWC. This data was of two types: drops into a Circulating Water Channel, and drops from a moving carriage into still water, simulating the current effect. Appendix A contains a full description of these experiments. As explained there, the data shows that these small sinkers reach horizontal current velocity almost immediately upon entering the water. The data shows that the larger the sinker the longer it takes to reach horizontal steam velocity; but even for the 250 lb sinkers, it reaches the stream velocity very quickly. It is felt that full size sinkers would not come to stream velocity as quickly; but only further testing can definitely answer this question.

In lieu of actual measurement, the offset due to current can be determined if two things are known: the time of descent, Dt, and the horizontal velocity of the sinker due to current with respect to time, u(t). Ignoring the variations in offset found in still water, the following formula holds:

$$\text{offset} = \int_0^{Dt} u(t)\,dt$$

Since considerable data were taken on the descent time, the next section discusses this and compares it to theoretical expectations. Two estimates of maximum possible offset due to current are given, based on these descent times and the above equation.

4.1.1 Time of Descent and Terminal Velocity

The descent times (Dt) for almost all the NSWC and CEL drops were recorded, as explained in Section 2, the description of the experiments, and the raw data are given in Appendix B with the offset data. The present section attempts to quantify offset due to current when the sinker is released at the water surface only, so the average Dt for each sinker at a drop height of 0, with no chain attached, is given in Table 4-1. These figures are considered quite reliable, since the variance around each mean is very small.

TABLE 4-1. SINKER DROP DESCENT TIMES AND VELOCITIES

SINKER		Dt(sec)			$V_t$eff (ft/sec)		V_t (theoretical) (ft/sec)		
NO.	WT.	24'	56'	88'	24-56'	56-88'	C_d=1	C_d=1.5	C_d=2
N S W C									
2	525		7.31				9.02	7.37	6.38
4	267	3.21	7.11		8.21		8.59	7.02	6.08
5	1090		7.42	11.39		8.06	9.74	7.95	6.90
6	490	3.69	7.97		7.48		8.59	7.02	6.08
C E L									
11	950	3.7	7.9		7.62		9.51	7.77	6.73
12	890		8.2				9.41	7.69	6.66
14	960	3.8	7.95		7.71		9.41	7.69	6.58
15	980		8.2				9.51	7.77	6.73
6	5800		6.7	9.1		13.30	12.66	10.34	8.96
7	5600		6.6	9.5		11.03	12.80	10.46	9.06
8	5600		6.45	9.1		12.09	12.73	10.40	9.01
10	5600		6.65	9.95		10.32	12.58	10.28	8.90
1	8200	2.6	5.5	8.2	11.03	11.85	14.66	11.97	10.37
2	8200		5.3				14.72	12.03	10.42
3	8250		5.6				14.72	12.03	10.42
4	8200		5.6				14.66	11.97	10.37
DTNSRDC									
A	2.5			29.0			3.88	3.17	2.75
B	16			23.0			5.49	4.49	3.89
C	60			20.7			6.72	5.49	4.76
D	267			11.4			8.59	7.02	6.08
E-	490								
	482			12.0					
	525								
F	1090			10.9			9.74	7.96	6.90

These figures are used to validate the following theoretical equation for Dt, and to show that a sinker drag coefficient (C_d) of about 1.5 is reasonable. Of course there are many uncertain factors in the equation; the C_d is one, and the sinker's projected area which is assumed constant, actually varies as the sinker descends due to fluttering. Hydrodynamic masses for sinkers are also uncertain. (See Section 4.2 and Appendix A for a further discussion of these topics.) Therefore, a rigorous statistical validation is not aimed for; rather, it is shown that the empirical data agrees well with the results of the equation.

Starting with the following well-known equation for acceleration due to gravity in a fluid:

$$W_w + 1/2(\rho C_{d_v} A_v v|v|) + (m+m_{H_v}) \frac{dv}{dt} = 0$$

where:

C_{d_v} = Vertical Drag Coefficient
A_v = Cross Sectional Area Presented to the Vertical
m = Mass of sinker
m_{H_v} = Hydrodynamic Mass for Vertical Motion
W = Weight of sinker in air
W_w = Weight of Sinker in Water

The equations for vertical velocity (v) and descent time (Dt) of a sinker have been derived by Patton (Reference 3). Letting $K_v = 1/2\ \rho\ C_{d_v} A_v$, they may be expressed as

$$V = \sqrt{W/K_v}\ \tanh\left(\sqrt{\frac{K_v W}{(m+m_{H_v})^2}}\ t\right)$$

$$D_t = \sqrt{\frac{(m+m_{H_v})^2}{K_v W}}\ \cosh^{-1}\left[\exp\left(\frac{K_v Y}{m}\right)\right]$$

Furthermore, letting time go to infinity in the velocity equation gives the expression for terminal velocity (V_t):

$$V_t = \sqrt{W/K_v}$$

Unlike the preceding equations, the expression for V_t contains no hydrodynamic mass term, since the body is not accelerating after V_t is reached. Since no reliable estimate of hydrodynamic mass exists for the sinkers, the V_t rather than Dt is used for comparison between the data and the theoretical expectations.

Table 4-1 gives the empirical V_t's ($V_t$eff), derived from the Dt data, and three estimates of V_t (V_t (Theoretical)) given by the

above equation. The three theoretical estimates are made using C_d's of 1, 1.5, and 2. The value of 1.5 is considered a reasonable estimate of a sinker's C_d (Reference 4) and the other two figures are included to give an idea the sensitivity of the V_t to the C_d.

The empirical figures are derived as follows. According to the equations for Dt and distance travelled, each sinker should be travelling at a constant velocity, V_t, after 24 ft. Therefore V_t is (for instance) the distance travelled from 24 to 56 ft. (32 ft) divided by the difference in descent times. Similarly, estimates are obtained between 56 and 88 ft. Admittedly, one of the 5000 lb. sinkers at CEL fell as much as 3 ft/sec faster than predicted. Although this aberration is unexplained, such a variation in experimental data is not unreasonable. Generally, it can be seen that with C_d = 1.5, the theoretical values agree well with the empirical results.

In the next section, the empirical Dt's are used in preparing the maximum offset tables. The theoretical values have been presented here only to lend credence to the empirical ones.

4.1.2 Maximum Possible Offset Due to Current

The data for the small sinkers show that they reached stream velocity almost immediately upon entering the water. Taking the horizontal velocity, u(t), as a constant equal to U (current velocity) the offset equation gives the maximum possible offset due to effect of the current. Thus,

$$\text{maximum possible offset} = \int u(t)\,dt = \int_0^{Dt} U\,dt = Ut\Big]_0^{Dt} = UDt$$

The values for maximum offset thus derived are given in Table 4-2 for all the sinkers, using the empirical descent times. These figures are experimentally validated for the small sinkers only; it is expected that the actual offsets for the larger sinkers would be less.

More reasonable estimates of maximum offset might be derived using the following theoretical equation for u(t):

$$u(t) = \frac{U^2\left(\frac{\alpha}{m+m_h}\right)t}{1 + U\left(\frac{\alpha}{m+m_h}\right)t}$$

where

$$\alpha = \frac{\rho\, C_{d_H}\, A_H}{2}$$

TABLE 4-2. MAXIMUM POSSIBLE OFFSET DUE TO CURRENT BASED ON EMPIRICAL DATA

SINKER		Offset (ft) Water Depth								
		24 ft			56 ft			88 ft		
NO.	WT.	1 kt	2 kt	4 kt	1 kt	2 kt	4 kt	1 kt	2 kt	4 kt
N S W C										
2	525				12.3	24.7	49.4			
4	269	5.42	10.8	21.7	12.0	24.0	48.0			
5	1090				12.5	25.1	50.1	19.2	38.5	76.9
6	490	6.23	12.5	24.9	13.5	26.9	53.8			
C E L										
11	950	6.25	12.5	25.0	13.3	26.7	53.3			
12	890				13.8	27.7	55.4			
14	960	6.41	12.8	25.7	13.4	26.8	53.7			
15	980				13.8	27.7	55.4			
6	5800				11.3	22.6	45.2	15.4	30.7	61.4
7	5600				11.1	22.3	44.6	16.0	32.1	64.1
8	5600				10.9	21.8	43.6	15.4	30.7	61.4
10	5600				11.2	22.5	44.9	16.8	33.6	67.2
1	8200	4.4	8.8	17.6	9.3	18.6	37.1	13.8	27.7	55.4
2	8200				9.0	17.9	35.8			
3	8250				9.5	18.9	37.8			
4	8200				9.5	18.9	37.8			
DTNSRDC										
A	2.5							49.0	97.9	196
B	16							38.8	77.7	155
C	60							34.9	69.9	140
D	267							19.2	38.5	77.0
	490									
E	482							20.3	40.5	81.0
	525									
F	1090							18.4	36.8	73.6

This is derived from the basic equation for acceleration of a sinker due to current in Appendix A. Again, a problem with this equation is that it involves the hydrodynamic mass, for which we have no data. However, a cursory examination reveals that the maximum u(t) is given using a hydrodynamic mass of 0. Since this produces the maximum offset, it was used to find the figures given in Table 4-3. Since the true hydrodynamic mass is certainly greater than 0, it may be expected that these values are somewhat higher than the true ones; but only further testing can establish (or disprove) this. A C_d of 1.5 is used.

It is not surprising that the offsets predicted by the equation and presented in Table 4-3 are smaller than the maximum possible offsets (UDt) in Table 4-2. Small sinkers are theoretically expected to approach stream velocity much more rapidly than larger sinkers. This fact in conjunction with the long fall times (up to 29 seconds for a Type A sinker in 88 feet of water) make the offset values predicted for small sinkers very close to the maximum offset, UDt.

These tables are presented as the best estimates possible for offset due to current given the limited extent of present knowledge. It should also be noted that they do not include the random offset in still water discussed in Section 3; this should be added on to find the total possible offset. Finally, these figures are for sinkers with no chain attached; it is expected that chain should reduce the offset due to current.

4.2 Sinker Motion in Still Water

4.2.1 Observations of Sinker Motion

As stated earlier, sinker drops at NSWC were recorded on film, and observed from a glass bottom boat. The films were thoroughly analyzed for two sinker drops; the results of the study are found in Figures 4-1a and b and 4-2a and b. It should be noted that this is a distorted two-dimensional projection of the actual three-dimensional motion. No information could be obtained concerning the third dimension; the film is not clear enough to allow a study of such visual clues as foreshortening of the sinker. As an example, Figure 4-1a shows the sinker landing 1 ft. away from the center; the actual offset for this drop was 9 ft. Thus, significant motion definitely occurred in the third dimension.

These plots indicate that the sinker initially fell straight down for about 10 ft., then oscillated or fluttered from side to side. This agrees with the motion observed from the boat, except that the observers felt the initial slide, preceeding the flutter motion, was of greater magnitude than the following oscillations. It is entirely possible that much of this motion was in the third dimension, and so cannot be seen by the cameras. The idea that most of the offset is due to the initial slide is borne out by the fact that the sinkers were biased in the same direction at every depth. If, instead, the oscillations continued to be of equal magnitude as the initial one, veering first to one side of the tank, then the other, the directionality would probably be different at each depth.

TABLE 4-3. CALCULATED SINKER OFFSET DUE TO CURRENT

SINKER		Offset (ft) Water Depth 24 ft			56 ft			88 ft		
NO.	WT.	1 kt	2 kt	4 kt	1 kt	2 kt	4 kt	1 kt	2 kt	4 kt
NSWC										
2	525				5.53	14.7	35.7			
4	267	1.84	5.28	13.7	6.11	15.6	36.8			
5	1090				4.88	13.5	33.9	9.25	24.1	57.5
6	490	1.88	5.54	14.7	6.20	16.3	39.4			
CEL										
11	950	1.62	4.95	13.6	5.47	14.9	37.0			
12	890				5.89	15.9	39.1			
14	960	1.65	5.05	13.9	5.41	14.8	36.9			
15	980				5.69	15.5	38.4			
6	5800				2.80	8.63	24.0	4.66	13.7	36.5
7	5600				2.79	8.58	23.8	5.10	14.8	39.1
8	5600				2.85	8.68	23.8	5.02	14.5	38.0
10	5600				2.95	8.98	24.6	5.71	16.4	42.4
1	8200	0.53	1.83	5.84	2.02	6.39	18.2	3.97	11.8	31.9
2	8200				1.83	5.86	16.9			
3	8250				2.00	6.36	18.3			
4	8200				2.08	6.57	18.7			
DTNSRDC										
A	2.5							45.2	93.4	190
B	16							33.8	71.6	148
C	60							28.1	61.3	129
D	267							11.7	28.2	63.8
	490									
E	482									
	525									
F	1090							8.68	22.7	54.5

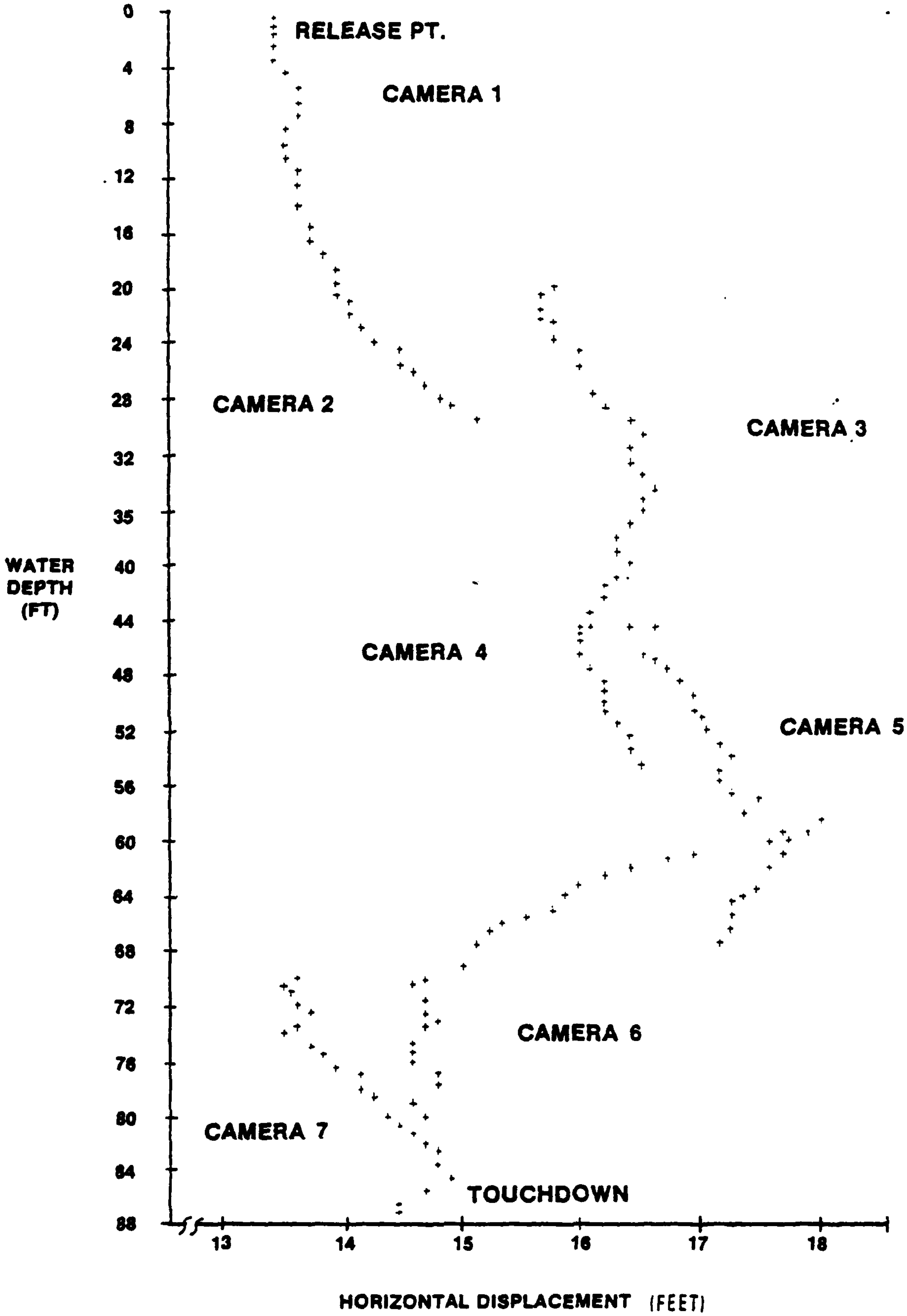


FIGURE 4-1a 1000 lb. SINKER MOVIE PLOT

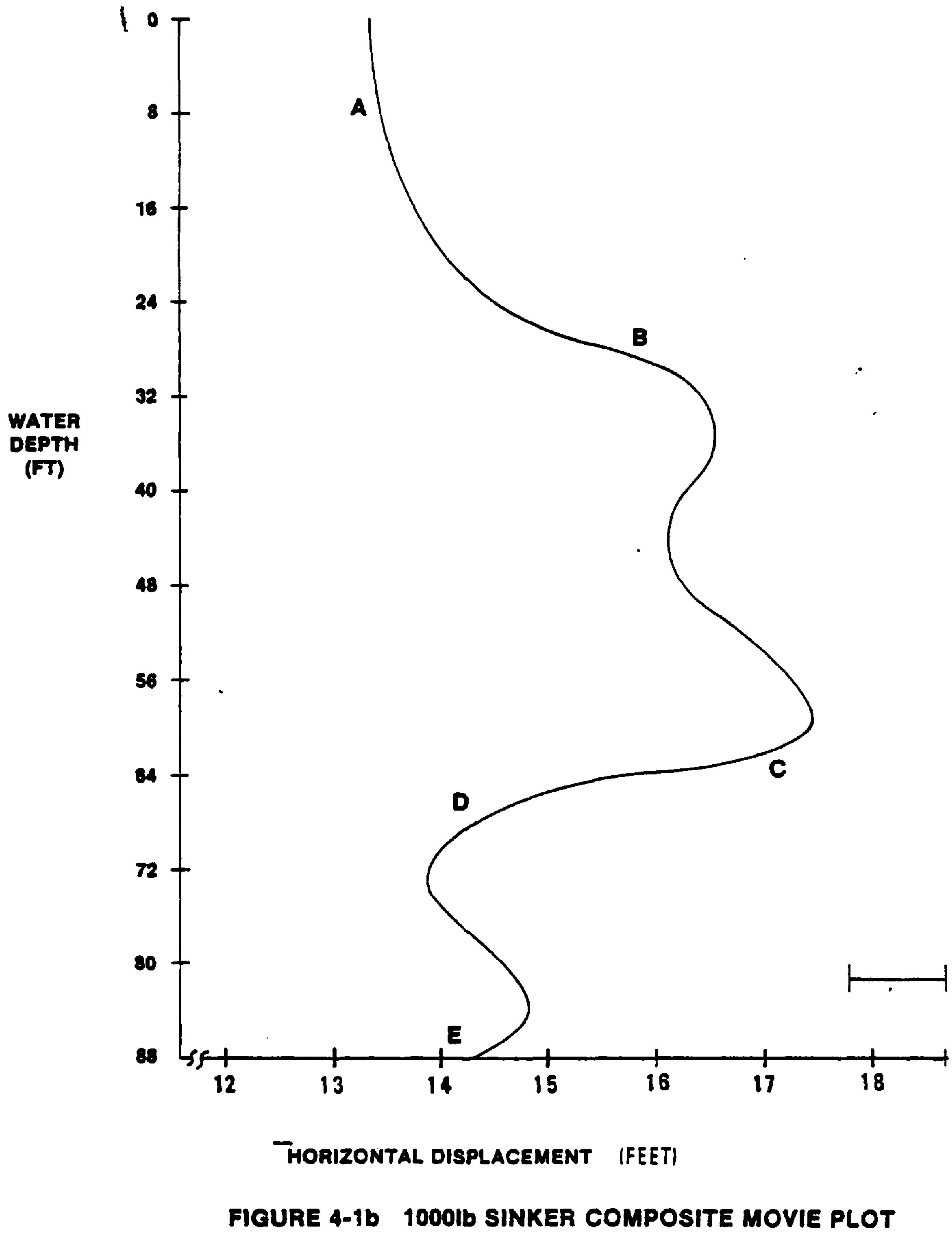


FIGURE 4-1b 1000lb SINKER COMPOSITE MOVIE PLOT

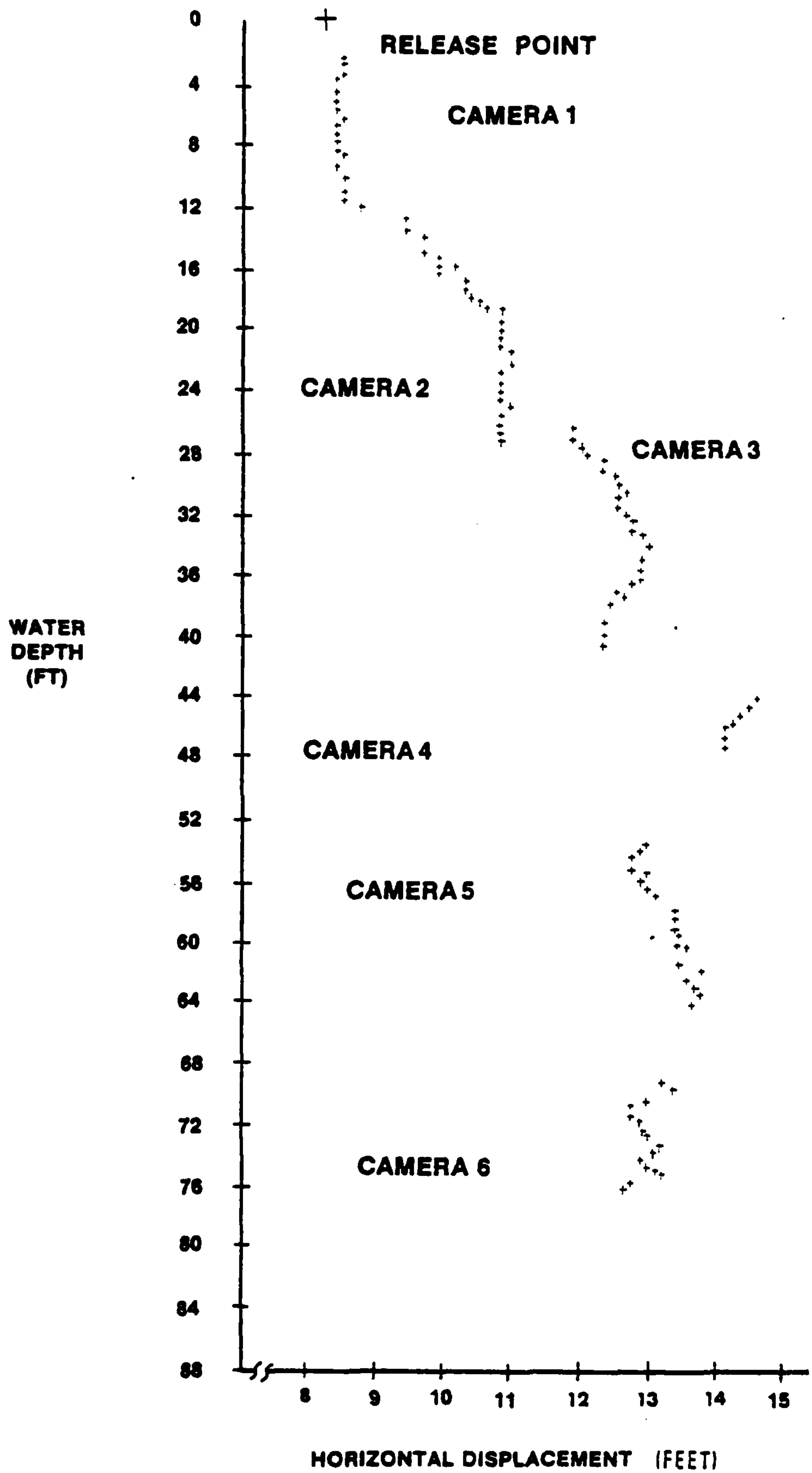


FIGURE 4-2a 60 LB. SINKER MOVIE PLOT

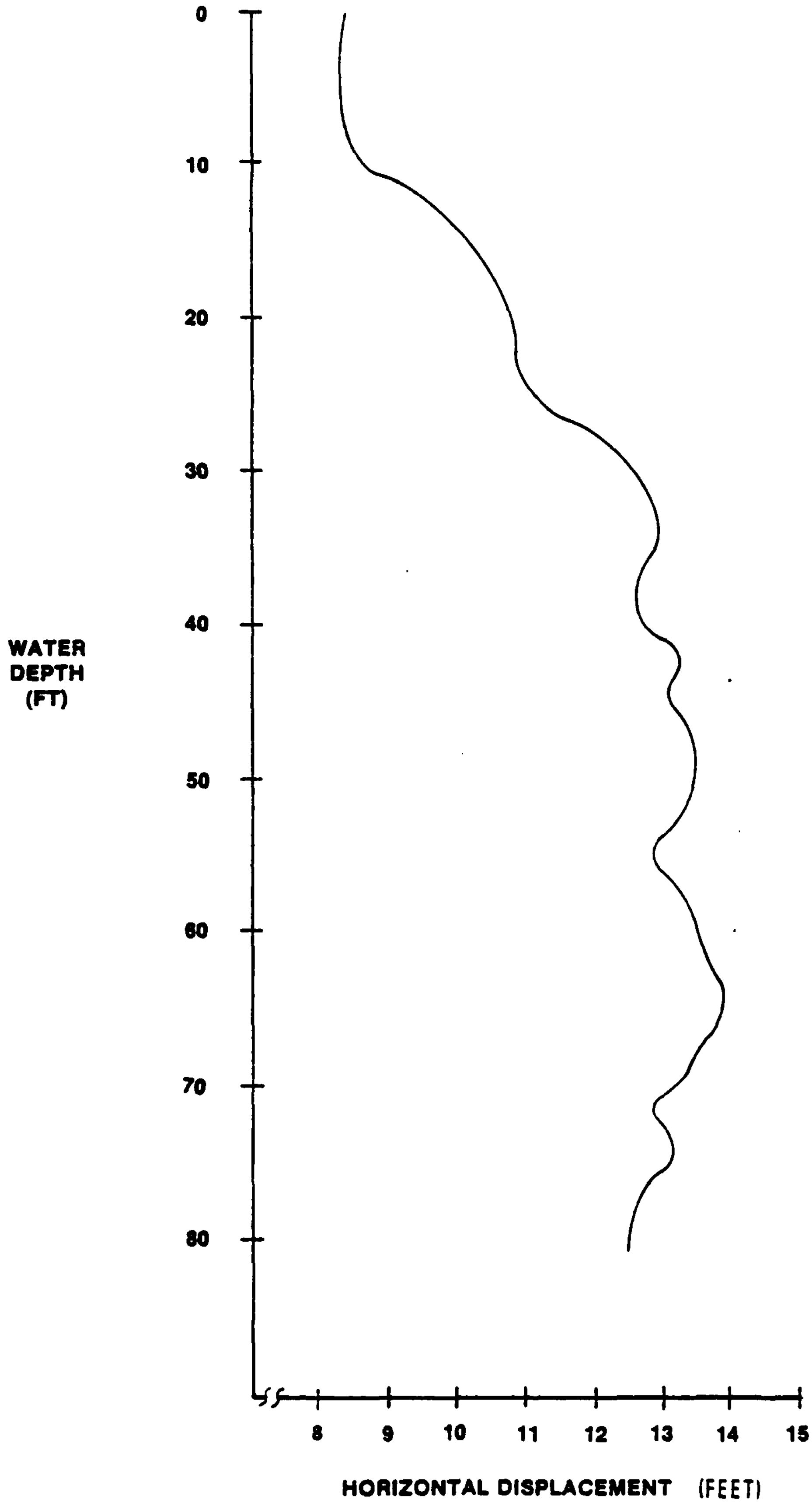


FIGURE 4-2b 60 lb. SINKER COMPOSITE MOVIE PLOT

The CEL sinker drops were observed for about the first 20 ft., and appeared to fall straight down during this time. The murkiness of the water made it impossible to see whether fluttering occurred afterwards. As explained previously, the CEL sinkers were made specially so as to have minimal center of gravity displacement while the NSWC sinkers definitely had such displacement.

The next section looks at this and other possible influences from a theoretical point of view, to put the foregoing discussion in perspective and provide a groundwork for possible future researchers.

4.2.2 Possible Mechanisms Affecting Sinker Motion

This section synopsizes the factors which may be significant in determining sinker motion.

The center of gravity location is undoubtedly important. Due to inhomogeneities in most standard sinkers, the center of gravity (c.g.) and center of buoyancy (c.b.) are not coincident. Sinkers dropped on their sides landed upside down in all cases, indicating the c.g. may be displaced above the c.b. Horizontal displacements of the c.g. from the centroids have also been quantified. The fact that the perturbations observed during the fluttering were nearly always insufficient to flip the sinker indicates that the c.g./c.b. vertical separation is probably relatively small. Aberrations in the basic geometric form, including chipped edges, rounded corners and non-parallel faces, could also affect the falling sinker.

As the sinker moves through the water it is subjected to hydrodynamic pressure forces. If, during the falling motion, the sinker becomes tilted at some angle to the horizontal, then the motion of the body may be explained like an airfoil. The tilt may be thought of as an angle of attack and the resultant flow around the sinker produces velocity changes of the fluid particles above and below the sinker. The velocity along the base of the sinker is decreased producing a relative increase in pressure, while the upper face experiences increased velocity and decreased pressure (suction). Due to these differential pressures, there is a resultant lift force. The effective point at which this resultant force acts varies with the sinker attitude, but in general it tends to orient the sinker back towards the horizontal.

As the leading edge rises due to the lift, the angle of attack increases and produces a corresponding increase in the lift force. This trend may continue until the pressure gradient due to the deceleration of flow past the after section of the suction side becomes too steep. The adverse pressure gradient causes boundary layer separation, the formation of vortices and a dramatic loss of lift. This phenomenon is known as stall and generally occurs at an angle of attack between 15^{o} and 20^{o} for a streamlined body, and somewhat less for a bluff body.

Boundary-layer transition also increases the fluid viscous forces on the body. Form drag, which is the resultant streamwise component of the pressure forces on the sinker, becomes significant. As the vortices created by the boundary layer separation move downstream there is considerable suction, which causes a large pressure drag on the sinker. Resonance with vortex shedding is unlikely in this flow situation. This is more characteristic of steady flow past a body and is responsible for phenomena such as cable strumming. The proportionality constant between the predominant frequency of vortex shedding (f_s), and the free stream velocity (U) divided by the sinker width (L), is the Strouhal number (S) or

$$S = \frac{f_s L}{U}$$

For flow around a cylindrical body with a Reynolds number greater than 10^4 the Strouhal number is essentially constant and equal to 0.21. Using this as an approximation with an average vertical velocity for a typical falling sinker yields a shedding frequency of 0.63/sec or a period of 1.6 sec. However, it may be that the harmonic variation in flow conditions due to stall flutter would tend to prevent the formation of vortices at this frequency.

When the fluid particle velocities past the sinker are less than critical the viscous drag appears as skin drag. Once the particle velocities reach a critical value and boundary layer separation occurs, turbulent friction must also be considered. The relatively large Reynolds numbers ($Re \approx 10^6$) associated with the flow around a non-streamlined body such as the falling sinker are indicative of the likelihood of turbulent flow especially when the horizontal velocity component due to fluttering is superimposed on the general falling motion.

The actual sinker motion is probably the result of a complicated interaction of these phenomena and the relative predominance of any one factor is presently indeterminate. However, in order to put the foregoing discussion in perspective, the following postulation is suggested.

The initial motion of the sinker as it begins its descent through the water column may be governed by gravitational forces and a static instability. The instability is a result of the center of gravity/center of buoyancy moment which may cause the sinker to tilt. The sinker velocity increases due to gravitational acceleration and decreased hydrodynamic resistance as it falls off in the direction of tilt with a significant horizontal velocity component. Once the fluid velocities past the sinker reach a critical value, this early transient phase of the motion gives way to fluttering motion with small horizontal amplitudes superimposed on a more nearly vertical descent. The fluttering may be a result of alternate lift and stall phenomena affecting the sinker much as an airfoil. This action may be intensified by the c.g./c.b. moment. The viscous effects of skin drag, turbulent drag, and form drag naturally tend to dampen this type of motion.

Whether the flutter is confined to a single plane or not is unclear; however, classical potential flow theory as presented by Lamb (Reference 5) suggests the possibility of a helical or spiral type motion of a falling body when analyzed in six degrees of freedom. There is little data to support or negate such a motion. Also, present knowledge gives little indication of the magnitude of the flutter.

In order to further investigate the possible effects of sinker inhomogeneities, calculations were made to determine the instantaneous angular acceleration due to the center of gravity/center of buoyancy moment. The calculations were based on the c.g./c.b. separation in the horizontal plane as determined by measurement for the five sinkers used in the NSWC tests. (See Figure 3-18.) The angular acceleration is linearly related to the c.g./c.b. separation but inversely proportional to a complex function involving the lateral dimensions and buoyant weight of the sinker.

If the sinkers are ranked based on increasing c.g./c.b. separation the order is: 6, 4, 2, 1, and 5. With respect to increasing offset distance on the bottom, the ranking is: 4, 2, 6, 1, and 5. Based on the calculations, the ranking of sinkers' instantaneous acceleration about the x axis is: 6, 4, 2, 5, and 1 and about the y axis is: 6, 5, 1, 2, and 4.

Before drawing conclusions a few cautionary notes are in order. First, the values calculated are instantaneous accelerations, valid only for one sinker attitude. Secondly, the mass moment of inertia of the sinkers used was that for a block of homogeneous material, with the addition of the moment of inertia of the entrained fluid. Lastly, the size (weight) ranking of the sinkers is: 4, 1, 6, 2, and 5 and is not necessarily independent of c.g./c.b. separation or offset on the bottom.

The results indicate that an increase in the c.g./c.b. separation does not translate directly into increased instantaneous angular acceleration (due to the effect of sinker dimensions). Although the rankings based on increasing c.g./c.b. separation and increasing offset distance correlate well, this is not the case when comparing the offset distance with the angular acceleration rankings. In fact the ranking for angular acceleration about the y axis shows more of a reverse correlation. That is, for increasing instantaneous angular acceleration about the y axis the offset distance on the bottom is decreasing. This may indicate that once a falling sinker tilts and attains a horizontal velocity component, that a larger angular acceleration may cause further tilting and produce the flow conditions necessary to initiate the stall flutter motion sooner, resulting in a smaller horizontal offset. This explanation remains purely conjectural based on the limited data available.

5.0 CONCLUSIONS

1. Equations were developed by regression based on circular normal σ's of all test data which approximate giving 95% confidence circles for sinker offset in terms of sinker size, depth and height of drop above water. These are given in Table 3-3 (page 50).

2. Approximate one standard deviation and 95% confidence circles for sinker offset for the most important classification of sinker size and water depth, at a drop height of 3 feet, are as follows:

Radius of One Standard Deviation and 95% Confidence Circle for Sinker Offset (ft)

Sinker Size	Depth (ft)	
	24	56-88
< 1000 lb. (NSWC & CEL)	r_{95} = 2.54	r_{95} = 5.45
	r_{σ} = 1.04	r_{σ} = 2.22
≧ 1000 lb. (NSWC & CEL & PRELIM)	r_{95} = 5.08	r_{95} = 11.49
	r_{σ} = 2.07	r_{σ} = 4.69

3. NSWC (Washington, D.C.) test factor effects:

a. As sinker size (250 - 1000 lbs) or depth (24 - 102 ft.) increased, so did offset.

b. As drop height (0 - 6 ft.) increased, offset decreased, relatively slightly but statistically significant at the .05 level.

c. Presence or absence of chain, and a small tilt to the sinker, did not have any significant effect.

d. Releasing the sinker on its side approximately doubled the offset.

4. CEL (Port Heuneme, California) test factor effects:

a. Sinker offset increased as depth increased from 24 to 56 feet; however, there was no significant difference between 56 and 88 feet.

b. Neither sinker size (1000-8500 lbs) nor drop height (0 - 6 feet) had a significant effect on offset.

c. The "8500" lb. sinker exhibited peculiarities not found in the other sinkers; most significantly, offset increased considerably as drop height increased; also, the individual sinkers varied considerably among themselves.

5. The difference between factor effects in NSWC and CEL cannot be attributed solely to the different sinker sizes because of the difference between the experimental situations: NSWC is a highly controlled experiment in an indoor tank facility, while the CEL experiment was conducted in the field.

6. Terminal velocities and times of descent for all sinkers agreed well with those predicted by a basic equation for gravitational acceleration of a body in a fluid. (See Table 4-1 on page 56).

7. Scale model sinkers reached stream velocity almost immediately when dropped in a current. No extrapolation to full-scale sinkers is justified due to the lack of dynamic similitude; therefore, no attempt was made to predict the effect of current on sinker offset. However, tables of maximum possible offset due to current, based on present knowledge, are included on pages 59 and 61.

8. All NSWC sinkers (the only ones whose orientations were recorded) exhibited statistically significant bias, i.e., the mean of the offsets was not directly under the sinker. Three of the five NSWC sinkers showed significant directionality, that is the distribution of offsets was not uniform through 360°. The remaining two NSWC sinkers were directional at the 90% confidence level.

9. The distribution of each sinker's offset is not different from the circular normal distribution. This is also true of all offsets taken as a whole.

10. When falling through the water column a sinker's motion is unsteady usually involving a "falling-leaf" fluttering probably due to a number of hydrodynamic factors, discussed in 4.2.1.

6.0 RECOMMENDATIONS

The following recommendations are offered for possible follow-up work in the ANPAR project.

1. If information on current effects is needed, tests should be conducted in a realistic ocean environment, with predictable tidal currents of reasonable magnitude. Attention should be given to the energy transfer effect at the surface (splash), which may cause the sinker to achieve stream velocity more quickly. This may be tested for by dropping sinkers from above and below the surface.

2. The approximate confidence circle estimates given here were obtained in more or less controlled conditions, and therefore are not directly applicable to actual field conditions. Validation using offset data from buoy tenders in the field is recommended.

3. It is clear from the present experiment that primary geometrical factors, i.e., nominal sinker dimensions of weight, height, etc., do not sufficiently define sinker motion. If further definition is required, preliminary theoretical and/or experimental work must be done to determine which of these may significantly affect hydrodynamic behavior: relatively small variations in nominal sizes, and secondary geometrical factors such as rough edges, rounding of corners, etc. Then a test under carefully controlled conditions, monitored in all 3 dimensions using the largest sinkers allowed by the test facilities, should be conducted using those factors identified as pertinent in the screening test.

4. A statistical study of the population of Coast Guard sinkers should also be conducted to determine how much variation in the significant factors exists among them.

5. Center of gravity location should be a factor in any future experiment, or at least should be recorded for each sinker.

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APPENDIX A

Rispin, Peter P., "An Investigation of The Placement Errors of Model Buoy Sinkers," DTNSRDC Report

Request for Work to be Performed by other Government Agency
#Z-51100 - 6202 - 6500

APPENDIX A

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

AN INVESTIGATION OF THE PLACEMENT ERRORS OF MODEL BUOY SINKERS

Peter P. Rispin

April 1977

Report SPD

TABLE OF CONTENTS

NOTATION

A	Cross Sectional Area of Body
C_d	Drag Coefficient on Body
d	Diameter of Body
D	Drag on Body
g	Acceleration Due to Gravity
K	Added Mass Factor
L	Length of Side of Sinker
m	Mass of a Body
m_h	Added Mass in Horizontal Motion
m_v	Added Mass in Vertical Motion
T	Total Time of Descent
t	Time
u	Horizontal Velocity
U	Speed of Stream
U_0	Initial Horizontal Velocity
v	Vertical Velocity
V	Terminal Velocity
V_0	Initial Vertical Velocity
W	Weight of Body
x	Horizontal Displacement
y	Vertical Displacement
α	Horizontal Drag on Body at Unit Velocity
β	Vertical Drag on Body at Unit Velocity
γ	Specific Gravity of Body

κ Initial Horizontal Drag to Mass Ratio

ρ Density of Fluid

σ Vertical Fall Parameter ; $-\beta V/m$

ABSTRACT

A number of experimental observations of the dropping of concrete sinkers into still and moving water are reported. These sinkers are models of larger sinkers used to position buoys by the United States Coast Guard. Sinkers of up to 1100 pounds (500 kg) were dropped into 88 feet (27 m) of water and high speed movies were taken. Smaller sinkers were dropped into the Circulating Water Channel at the David W. Taylor Naval Ship Research and Development Center to simulate drops into a current. A simple computer program was written to assist in evaluating the results. Terminal velocities, sinker motion characteristics, trajectory plots and sinker placement offsets are given.

ADMINISTRATIVE INFORMATION

This work was sponsored by the United States Coast Guard Research and Development Center, Groton, Connecticut under David W. Taylor Naval Ship Research and Development Center Work Unit Number 1548-087.

INTRODUCTION

The United States Coast Guard routinely drops buoys with concrete sinkers into water depths of up to 100 feet (30 m). Often, a current may be running at the drop site. For this reason and because the sinkers, not being streamlined bodies, tend to move laterally even in still water, the sinkers do not strike the sea floor directly below the drop point. The distance between the point on the sea floor below the drop point and the point at which the sinker strikes is the offset. The purpose of the investigation reported here is to characterize this offset in terms of sinker size, distance of fall, presence or absence of a restraining chain, strength of current and other variables.

DROPS INTO STILL WATER

The first experimental phase consisted of dropping various size sinkers into 88 feet (27 m) of water in the 100-foot tank at the Naval Surface Weapons Center, White Oak. Sinkers were dropped with and without a constraining chain flaked out above the drop point. This was to find whether or not a gross difference in offset and descent velocity existed due to the chain. The drop was timed by means of a stop watch and movies were taken. After impact the lateral distance between the sinker and the release point was measured.

The 100-foot tank is shown in Figure 1. It is 50 feet (15 m) in diameter and contains 100 feet (30 m) of clear fresh water. The major feature of the tank is a movable floor which can be raised or lowered to any depth. Camera positions are at 12.5-foot (3.8 m) intervals starting 12.5 feet below the water surface. Viewing ports are in similar positions around the tank. A walkway projects over the center of the tank at a height of 4 feet (1.2 m) above the water surface. A buoyant wooden platform was attached to the movable floor so as to cushion the impact of a falling sinker.

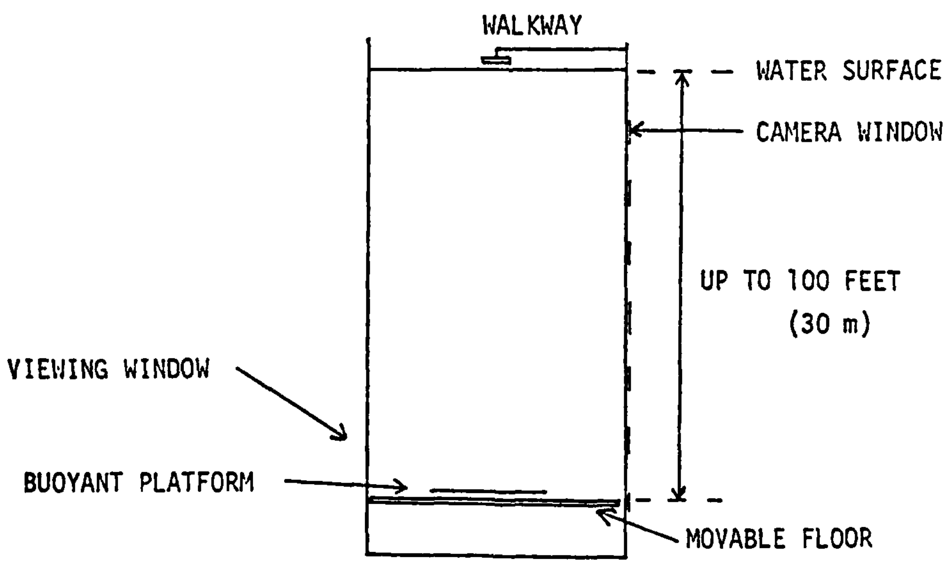

Figure 1 - 100 Foot Tank at NSWC

The sinkers were made of concrete and their weights in air varied from about 2 pounds (1kg) to about 1100 pounds (500 kg). They were made of concrete with specific gravity γ equal to 2.4 approximately. They were, roughly, rectangular parallelepipeds L x L x L/2 where L varied from 4 inches (100 mm) to 32 inches (0.8 m). Each had a metal eye-bolt protruding from the upper face. The sinkers are sketched in Figure 2 and some of their properties shown in Table 1.

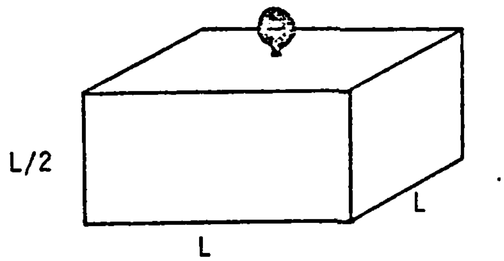

Figure 2 - Typical Sinker

TABLE 1 - NOMINAL SINKER PROPERTIES

SINKER		A	B	C	D	E	F	X
LENGTH L	inches	4	8	12	20	24	32	4
	m	0.10	0.20	0.30	0.51	0.61	0.81	0.10
WEIGHT IN AIR	pounds	2.5	16	60	250	500	1000	11.2
	kg	1.1	7.3	27	113	227	454	5.1

These are nominal values about which the actual values varied widely, especially those for the larger sinkers. For example, one type D sinker was 18 x 17.6 x 10 inches (0.46 x 0.45 x 0.25 m) and weighed 275 pounds (125 kg) while another was more of a pyramid. One face was 20 x 20 inches (0.51 x 0.51 m) while the other (top) face was 17.2 x 16.8 inches (0.44 x 0.43 m). The weight was 306 pounds (139 kg). A type E sinker

weighed 472 pounds (214 kg) while the only type F sinker weighed 1115 pounds (506 kg). A single lead sinker, type X, was also used. Some drops were made using a pair of type D sinkers tied together by a 3-foot (0.9 m) cord. This was done, for interest sake, to check on possible motions during descent.

The effects of chain attachment were investigated during some of the drops using type D. An 0.5 inch (13 mm) chain was flaked out on the overhanging walkway and followed the sinker as it fell.

Each sinker was suspended either just above or just below the water surface by means of an electrically operated release. The majority of drops were made from below the water surface so as to standardize the initial drop conditions. On a signal the release was actuated and the sinker began to fall. Meanwhile, a vertical array of movie cameras, one at each of the camera positions as mentioned above, was also actuated. The sinker fell approximately along the center line of the tank, and its motion was recorded by each of the cameras in turn. The sinker fell on or near a buoyant platform a few inches above the movable floor. This platform cushioned the impact of the falling sinker. The sinkers did not bounce or roll over on impact. They generally settled onto one side or other if they hit on an edge. An observer at the lowest viewing port timed the descent from the signal to impact on the platform and also noted any peculiarities of the sinker motion. The floor then was raised above the water level and the offset between the position of the centroid after impact and the position at release was measured.

This was carried out for about 50 drops, of which 37 were filmed. The movies were analyzed using a stop-action projector and the displacement of a point on the sinker was measured frame by frame. This was done by projecting a frame on a screen and marking a particular point on the image of the sinker. The next frame was then projected and the process repeated. The time interval was fixed at 1/16 seconds. These data were then converted into displacement-time and velocity-time tables and plots.

A second series of drops into still water was made from a moving carriage into still water, but because of the relative horizontal motion of the sinker it is reported in the next section.

DROPS INTO MOVING WATER

The objective of the second phase was to find the offset from the release point as a function of current speed and sinker size. Two separate experiments were carried out. In the first, sinker types A and B were dropped into the Circulating Water Channel at DTNSRDC. In the second, a type D sinker was dropped from a moving carriage into the Deep Water Basin, at DTNSRDC to simulate dropping a sinker from a fixed point into a constant current. This was done because the large sinker would cause damage if dropped into the Circulating Water Channel (CWC). At the same time it was desired that the largest possible sinker be used to minimize scale effects for extrapolation to larger sizes. The CWC has a fixed drop point and moving current. The carriage gave a moving drop point into fixed water. A simple linear transformation will be used to show the equivalence of the two approaches.

The Circulating Water Channel has a working section which is sketched in Figure 3. It is 9 feet (2.74 m) deep and 22 feet (6.7 m) across. The

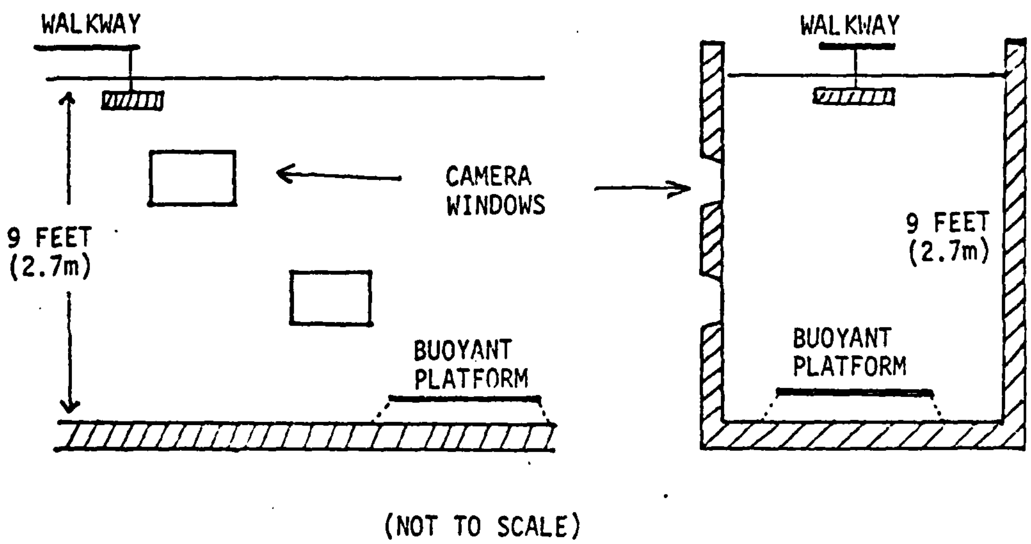

Figure 3 - Side and Front Elevation of Circulating Water Channel

flow was varied from 0 to 2 knots. (3.4 feet/second; 1.03 m/s). The horizontal flow velocity is constant to within 3 percent along a vertical line through the center of the channel. An example of the current profile is shown in Figure 4. The sinkers were released from a walkway suspended

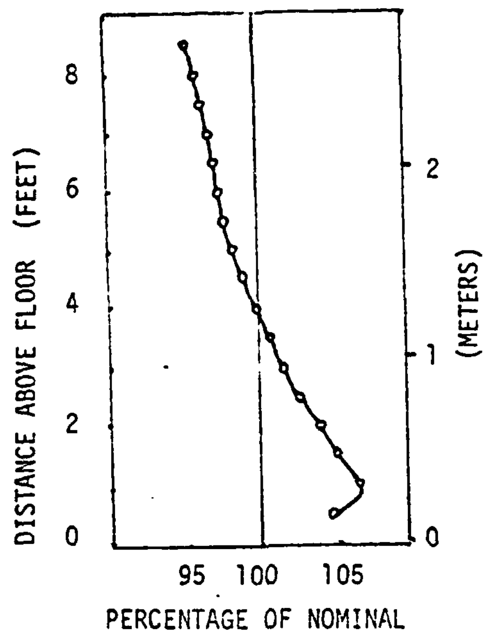

Figure 4 - Current Profile along a Vertical Line in the Circulating Water Channel

over the center of the channel. The sinkers were dropped with the bottom being about an inch (25 mm) above the water surface. The drops were filmed from two viewing ports in the side of the channel. The sinkers fell on or near a buoyant platform anchored to the floor. The time of descent was measured and the point of impact noted. Over 100 drops were made. The resulting movies were analyzed in the same manner as those taken during the first phase.

The second part of the second phase consisted of thirteen drops of a type D sinker into 22 feet (6.7 m) of water from a carriage moving at speeds up to 2 knots (3.4 feet/second, 1.03 m/s). The drop was from a height of about 3 inches (75 mm) and the resulting velocity was less than the terminal

velocity of the sinker. This is sketched in Figure 5. At the moment of

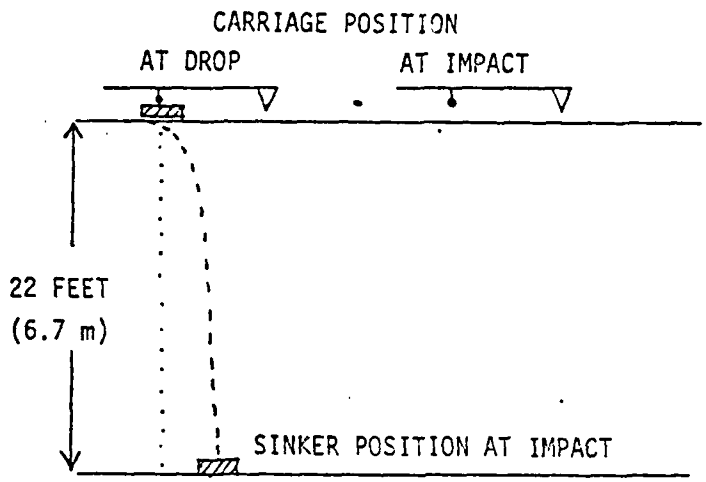

Figure 5 - Drop Into Deep Water Basin

release, the position of the moving carriage was noted. This was done by observing the position of a pointer fixed to the carriage relative to a scale fixed to the side of the towing basin. After the carriage was brought to a stop, it was backed up to the position at which the sinker was released. A thin wire rope with a locating float had been attached to the sinker before the drop. This was now pulled taut vertically and the horizontal offset from the point of release was measured. The accuracy with which the offset was estimated was approximately ± 3 inches (75 mm), based on careful sighting of the pointer by a second observer.

THEORETICAL ANALYSIS

To help in the interpretation of the results obtained in the drops described above, a simple uncoupled model was made for the vertical and horizontal motions of the sinkers. In each case only a single degree of freedom analysis was made, the effects due to tilting and spiralling of the sinkers during descent being omitted so as to render tractable the resulting

equations of motion. The sinkers were modelled as point masses moving under gravity and buoyancy and under the vertical and horizontal drag forces due to the fluid. The coordinate system is shown in Figure 6.

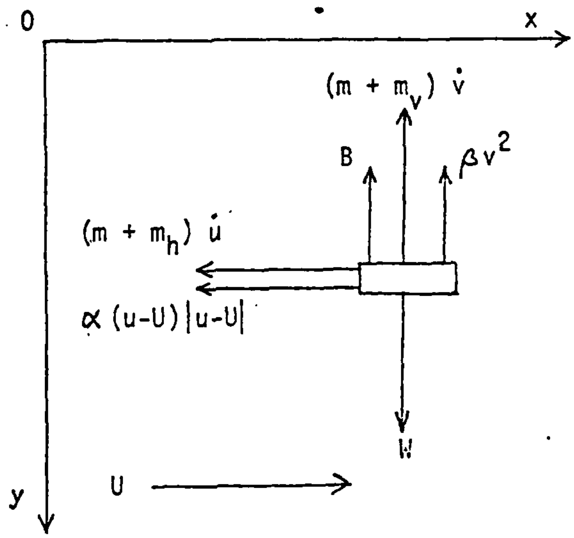

Figure 6 - Coordinate System and Balance of Forces

The point of release, assumed to be in water, is taken to be the origin 0. The x-axis is along the direction of the moving stream, and the y-axis is vertically downward. The added masses in the horizontal and vertical directions are m_h and m_v respectively.

ADDED MASS:

Values for the added mass coefficients of parallelepipeds are given by Patton[1]. Unfortunately, no data exist for parallelepipeds whose side ratios are those of the sinkers used here. Using Patton's data for a flat plate as an approximation,

$$m_h = 0.33\ m/\gamma$$

$$m_v = 0.75\ m/\gamma$$

[1] Patton, K.T., "Tables of Hydrodynamic Mass Factors for Translational Motion", ASME Paper 65-WA/UNT-2 (Nov 1965)

AD-A080 400 COAST GUARD RESEARCH AND DEVELOPMENT CENTER GROTON CT F/G 13/10
CHARACTERIZATION OF THE MOVEMENT OF A SINKER DURING DEPLOYMENT.(U)
OCT 77 W E COLBURN, J W CUTLER, R A MARCOLINI

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However, for a cube

$$m_h = m_v = 2.32\ m/\gamma$$

Purely as an ad hoc approximation to be used in further calculations, the following values will be used here,

$$m_h = 0.9\ m/\gamma$$
$$m_v = 1.3\ m/\gamma$$

HORIZONTAL MOTION:

Let $u = \frac{dx}{dt} = \dot{x}$ be the velocity in the x direction. Then the velocity of the sinker relative to the fluid is $u - U$, where U is the stream velocity. The assumption used here is that the horizontal force on the sinker is proportional to the square of the relative velocity and is positive if $u < U$ and negative if $u > U$

$$F = -\alpha\,(u - U)\,|u - U| \qquad (1)$$

with

$$= 1/2\,\rho\,C_{dH}\,A_H \qquad (2)$$

where ρ is the density of water

A_h is the projected cross-sectional area of the sinker in the horizontal direction

C_{dh} is the drag coefficient in the horizontal direction

This is assumed to be the only force acting in the horizontal direction. The unsteady forces, such as those due to changing attitude or to vortex shedding, are reflected in the experimentally determined drag coefficient. The equation of motion is then

$$(m + m_h)\frac{du}{dt} = -\alpha\,(u-U)\,|u-U| \qquad (3)$$

The initial conditions are

$$x = 0, \quad u = U_o \quad \text{at } t = 0 \qquad (4)$$

where U_o is any initial horizontal speed the sinker may be given at the beginning.

The solutions, derived in Appendix A, are

$$u = \frac{U_o + U\mathcal{K}t}{1 + \mathcal{K}t} = U - \frac{U-U_o}{1+\mathcal{K}t} \tag{5}$$

$$x = Ut - \frac{1}{\mathcal{K}}(U-U_o)\ \ln(1 + \mathcal{K}t) \tag{6}$$

where

$$\mathcal{K} = \alpha\ \frac{|U - U_o|}{m + m_h} \tag{7}$$

Thus as $t \to \infty$, equation (5) shows that $u \to U$, the stream velocity, and that the difference between u and U is proportional to the original difference, $U-U_o$. It also shows that the difference decreases slowly unless $\mathcal{K}$ is large, i.e $\rho C_{dH} A_H |U-U_o| / 2(m+m_h)$ is large. If $U_o = 0$ then $u/U = kt/1+kt$. To find the time it takes for u to reach 0.5U solve $0.5 = \mathcal{K}t/1+\mathcal{K}t$. Then $t_{1/2} = \frac{1}{\mathcal{K}}$ seconds.

Example: A cube of side 3 inches and of specific gravity 2.4 is dropped into a stream going at 3 feet/second. Plot u and x as functions of time if $C_{dH} = 1.5$. (ρ is 1.94 slugs/cubic foot)

$\alpha = 0.5 \times 1.94 \times 1.5 \times (0.25)^2 = 0.0909$ slug/foot

$m = 1.94 \times (0.25)^3 \times 2.4 = 0.0728$ slugs

$m_h = 2.32\ m/\ 2.4 = 0.0704$ slugs

$\mathcal{K} = 0.0909 \times 3\ /\ (0.0728+0.0704) = 1.91$

$$u = \frac{5.72\ t}{1 + 1.91\ t}$$

$x = 3t - 1.57\ \ln(1+1.91t)$

The time to reach U/2 is 0.52 seconds.

The plots are shown in Figure 7. Note that the speed rises sharply at first but then takes a long time to reach the stream velocity.

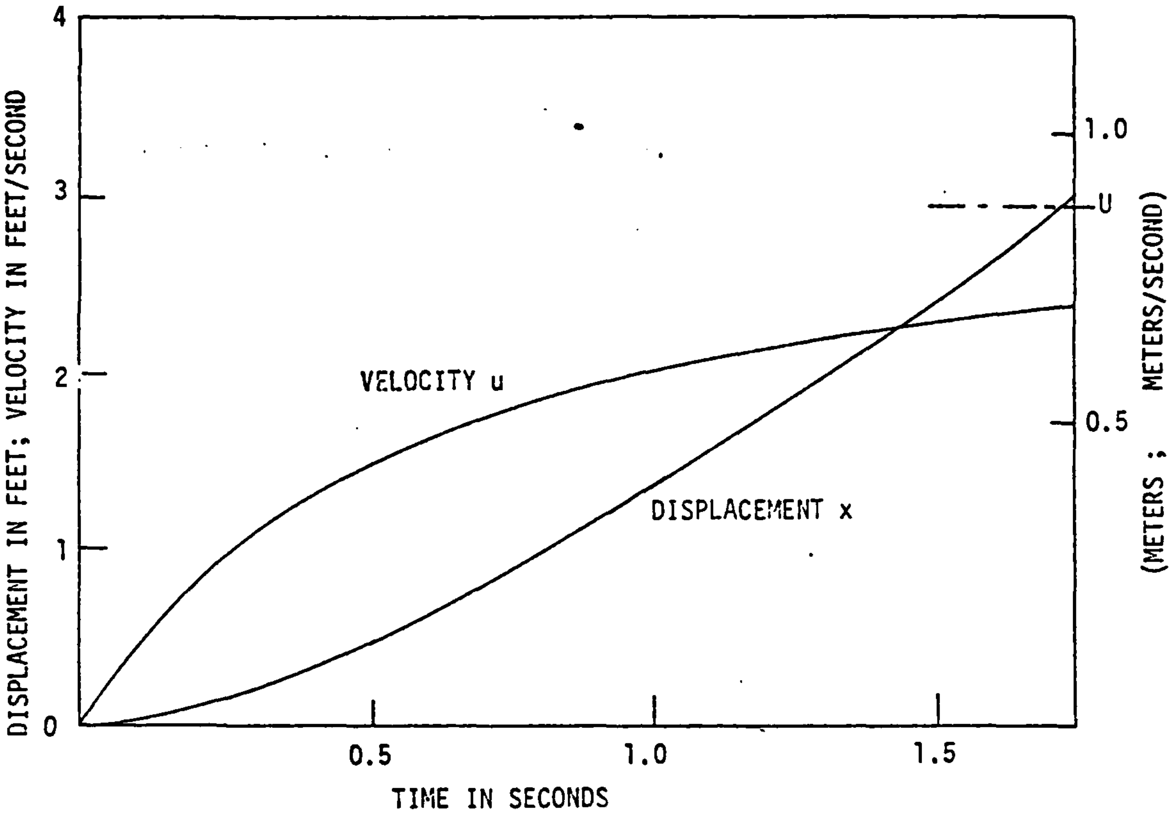


Figure 7 - Horizontal Velocity and Displacement Against Time for Example

VERTICAL MOTION:

Let $v = \frac{dy}{dt} = \dot{y}$ be the downward velocity. Let the vertical force be

$$F = mg - B - \beta v^2 \tag{8}$$

with

$$\beta = 1/2 \rho C_{dV} A_v \tag{9}$$

where g is the acceleration due to gravity

B is the buoyancy

C_{dv} is the vertical drag coefficient

A_v the cross sectional area for vertical motion.

The equation of motion is then

$$(m + m_h)\,\dot{v} = mg - B - \beta v^2 \tag{10}$$

$$= W^{\ell} - \beta v^2 \tag{10a}$$

where $W^{\ell} = mg - B$ is the weight in water of the sinker. Note that $\dot{V} = 0$ when

$$\beta v^2 = W^{\ell}$$

Then the velocity is constant and is called the terminal velocity.

$$V_T^{\,2} = W^{\ell}/\beta \tag{11}$$

Equation [10] can be integrated twice, as in Appendix A, with

$$y = 0,\ v = V_o \quad \text{at } t = 0 \tag{12}$$

as initial conditions to give

$$v = V_T \frac{1 - \lambda e^{-2\sigma t}}{1 + \lambda e^{-2\sigma t}} \tag{13}$$

$$y = V_T t + \frac{V_T}{\sigma} \ln \frac{1 + \lambda e^{-2\sigma t}}{1 + \lambda} \tag{14}$$

where $$\lambda = \frac{V_T - V_0}{V_T + V_0} \tag{15}$$

and $$\sigma = \frac{\beta V_T}{m + m_v} \tag{16}$$

Example: The cube of the previous example is dropped into water. Find v and y.

$$\beta = 0.5 \times 1.94 \times 1.5 \times (0.25)^2 = 0.0909 \text{ slugs/foot}$$

$$m = 1.94 \times (0.25)^3 \times 2.4 = 0.0728 \text{ slugs}$$

and since the sinker is a cube,

$$m_v = m_h = 0.0703 \text{ slugs}$$

$$W = mg = 0.0728 \times 32.15 = 2.34 \text{ pounds}$$

$$W' = \frac{\gamma - 1}{\gamma} W = \frac{1.4}{2.4} \times 2.34 = 1.36 \text{ pounds}$$

Then, from equation [11]

$$V_T = 3.87 \text{ feet/second}$$

and $\sigma = 2.46$

Therefore

$$v = 3.87 \frac{1 - e^{-4.92t}}{1 + e^{-4.92t}} \quad \text{feet/second}$$

$$y = 3.87t + 1.58 \ln \frac{1 + e^{-4.92t}}{2} \quad \text{feet}$$

The plots are shown in Figure 8. Note that the initial acceleration for vertical motion is greater than that for horizontal motion.

PARAMETERS IN TERMS OF THE TERMINAL VELOCITY

Combine equation [11] with equation [16] and note $W'/W = (\gamma-1)/\gamma$. Then

$$\sigma = \frac{\gamma - 1}{\gamma + K} \frac{g}{V_T} \tag{17}$$

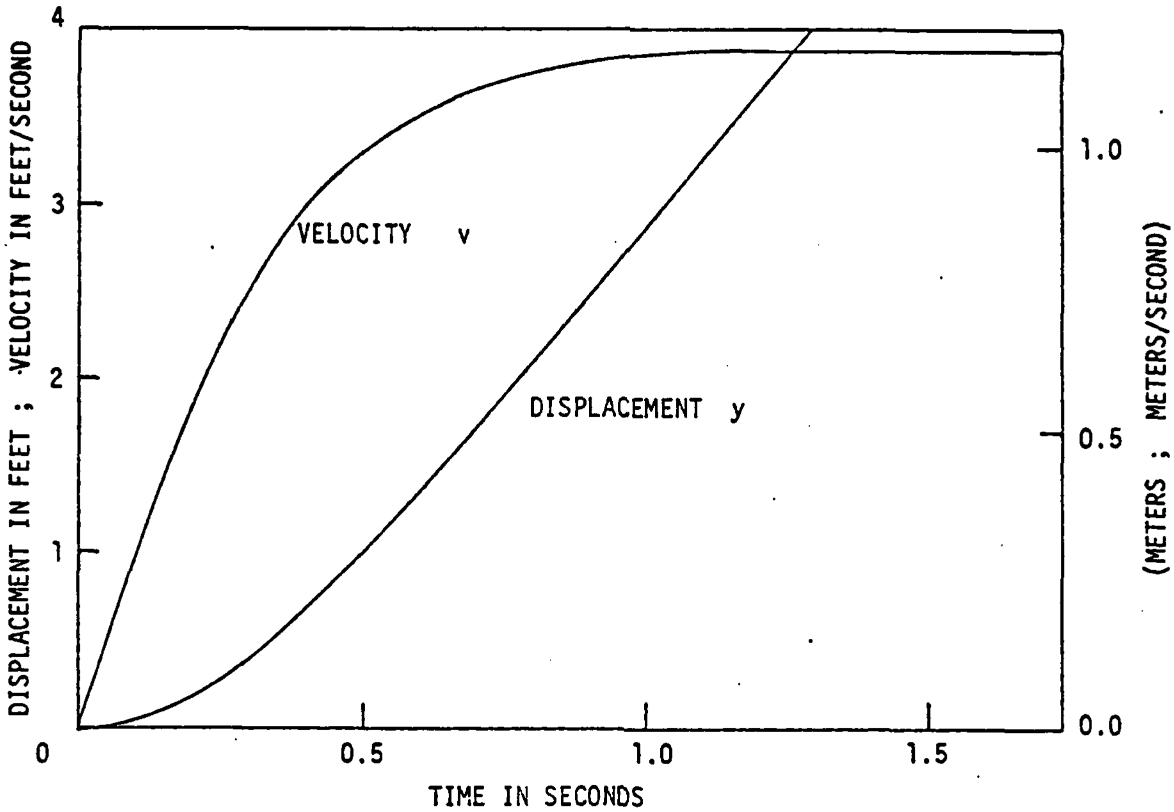


Figure 8 - Vertical Velocity and Displacement against Time for Example

where K is an added mass factor, as tabulated by Patton, which is defined as $K = m_v \gamma / m$. Equation [17] gives σ in terms of observed values. Finally equation [9] gives

$$\dot{C}_{dV} = \frac{2W'}{\rho A V_T^2} \tag{18}$$

These equations will aid in the interpretation of the data taken from both phases of the experiments.

PRESENTATION OF RESULTS

PHASE 1 NO CURRENT:

In general for the 50 drops made in this phase, the sinkers fell vertically with a low-frequency fluttering motion whose peak to peak amplitude was, approximately, two sinker widths. The bigger sinkers

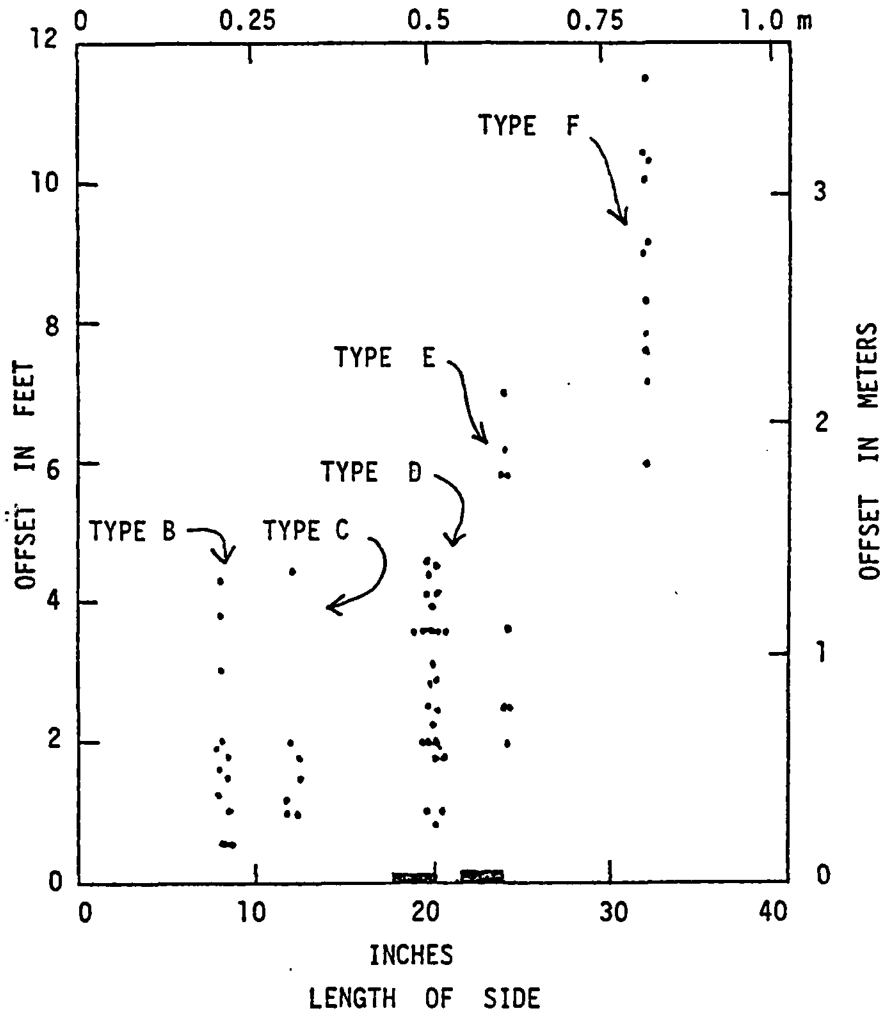


Figure 9 - Offset at a Depth of 88 Feet (27 m) for Types B through F

oscillated about three times in an 88-foot (27 m) fall. As can be seen from Figure 9, the offset is highly variable within a sinker group, while the offset grows with sinker size. The effects of chain were small in that the mean offsets of the drops with and without chain did not differ appreciably. The variability within a group is due to a number of reasons. First, the sizes of the sinkers of the same nominal size are quite variable as noted previously. The characteristics of a number of sinkers are shown in Table 2. The line on the abscissas of Figures 9 through 12 represents the range of variation for the side L. Second, the

TABLE 2 - PHYSICAL CHARACTERISTICS OF TYPICAL SINKERS

Weight in Air		Weight in Water		Specific Gravity	Length		Height	
pounds	kg	pounds	kg		inches	m	inches	m
267	121	160	73	2.50	18.3	0.46	9.8	0.25
482	219	280	127	2.39	24.0	0.61	9.8	0.25
490	222	287	130	2.41	24.0	0.61	9.8	0.25
525	238	307	139	2.41	24.0	0.61	10.8	0.28
1090	495	635	288	2.40	31.9	0.81	12.6	0.32

small angle at which the sinker starts out can change the initial phase of the flutter phenomenon. During the fall as the angle with the horizontal changes, the drag on the sinker changes. The leading edge stalls, drag rises and the oscillation reverses. It is not clear how this can be accounted for analytically. In an effort to extend the values obtained here to larger sizes a logarithmic plot of offset versus size is shown in Figure 10.

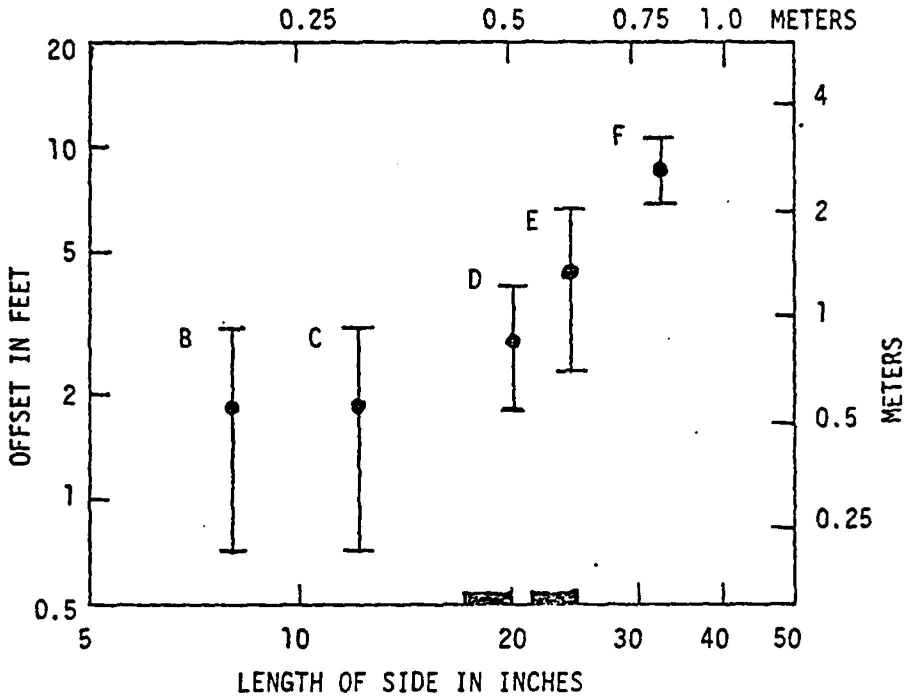


Figure 10 - Logarithmic Plot of Offset versus Size for 88 Foot Depth

The effect of the depth through which a sinker fell is shown in Figure 11 for the type-D sinker. The average velocity was calculated from the time of drop and the depth of the tank. Also the terminal velocity was taken from the movie footage taken at the 75-foot (23m) level. These are plotted in Figure 12. The effect of chain is seen to be so small as to be negligible. Drops for sizes larger than type-D were, therefore, done without chain. There is good agreement between the average and terminal velocities.

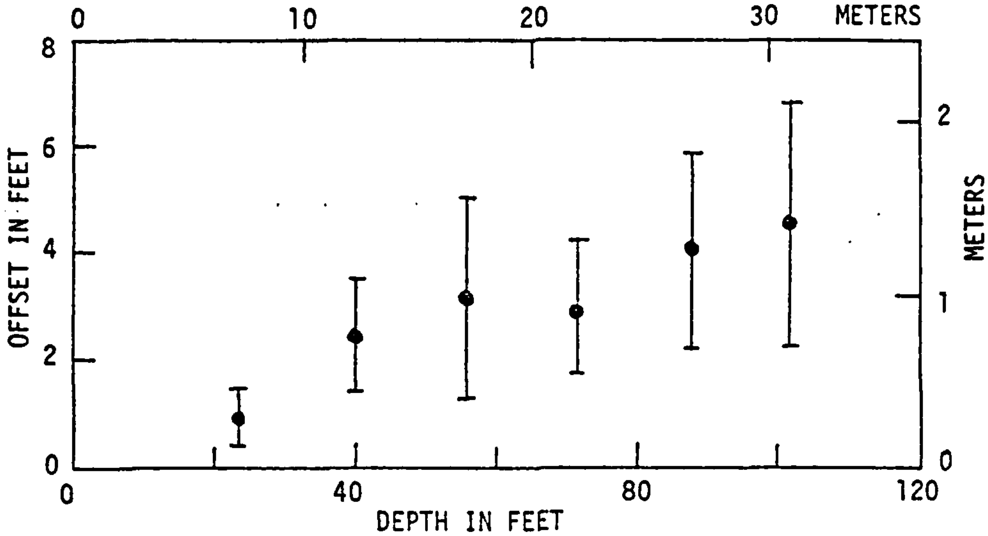


Figure 11a - Type D Sinker

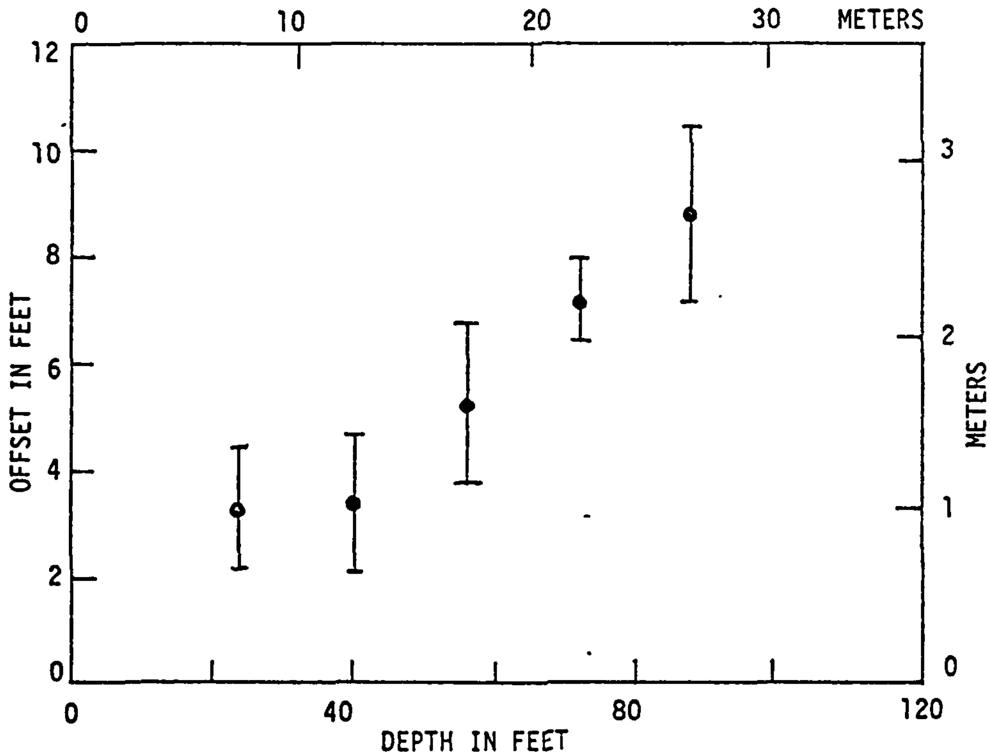


Figure 11b - Type E Sinker

Figure 11 - Offset versus Depth for Types D and E

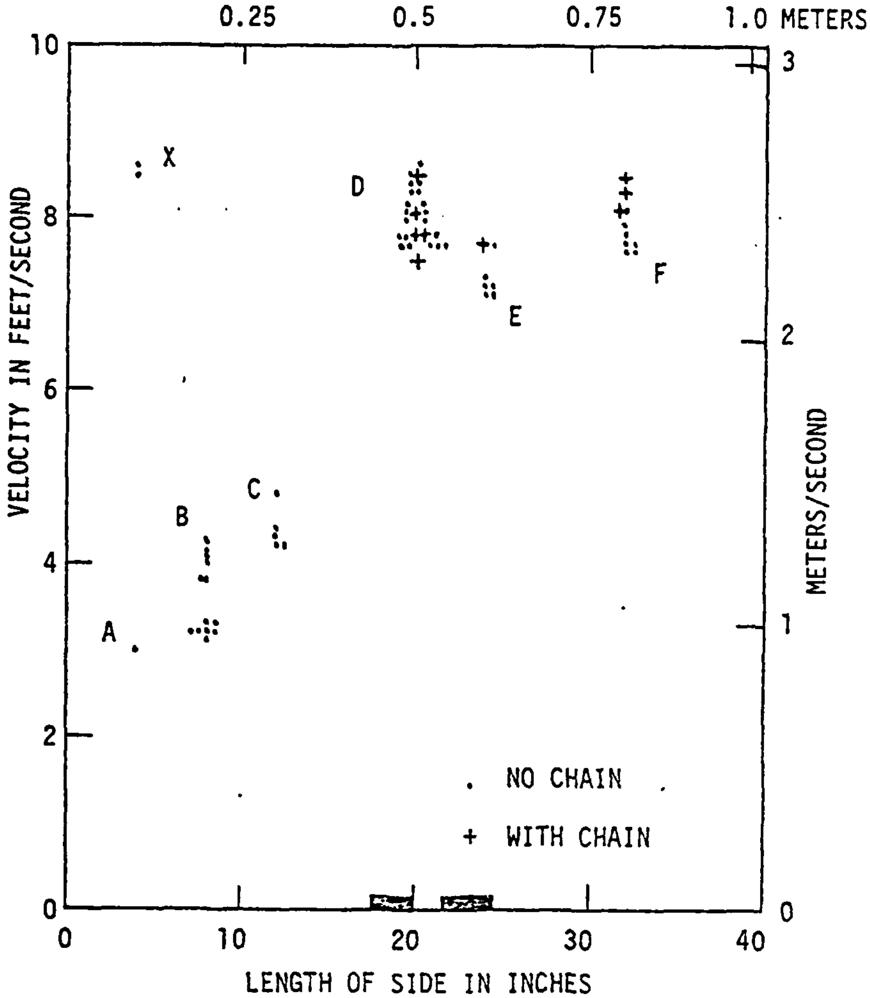


Figure 12 - Average Velocity versus Size for 88 Foot (27 m) Depth

From equation [14] it can be shown that

$$V_T - V_{av} = V_T \frac{\ln 2}{\sigma T}$$

which, for the sinkers in this experiment, comes to about 3 percent of V_T. Thus the difference between the average and terminal velocities is small in these experiments. The velocity is seen to rise with size and

then levels off. It is seen that type E has a smaller velocity than the smaller type D. However, the type D sinkers were over nominal size and weight, while the type E were under. In an effort to clarify this apparent anomaly, the vertical drag coefficient was calculated using equation [18]. The results are plotted in Figure 13. The value of C_{dv} given by Hoerner[2] is 1.50, though no Reynolds Number is given. It can be seen that the calculated values lie on both sides of Hoerner's value. The result for type D is, however, low while that for type E is high. A possible explanation is that type E is the most pyramidal of the sinkers, the larger face being downwards. Also plotted in Figure 13 is the vertical drag coefficient as a function of Reynolds Number,

$$R_n = \frac{LV_T}{\nu} \tag{19}$$

where ν is the kinematic viscosity of fresh water ($\nu = 1.21 \times 10^{-5}$ feet^2/second, 1.12×10^{-6} m^2/s). However, the sinkers oscillated many times during a drop. The drag coefficient would then be a function of oscillation frequency and other unsteady parameters which are not accounted for in the present simplified analysis.

Finally, the initial 1.5 seconds of motion for most of the sinker types were analyzed. The results are shown in Figures 14 through 19. In each figure, an average velocity over a number of runs is plotted against time. This is done by first finding the displacement as a function of time as described in the section "Drops into Still Water". The distance between successive positions of one corner of a sinker was divided by the time interval between frames and multiplied by the calibration factor for the camera set-up. This gave the velocity as a function of time. From the observed value of V_T and a value of σ calculated from equation [17], the theoretical value for the vertical velocity is plotted in Figures 14 through 19. Figure 14 includes an initial velocity of 15 feet/second (4.6 m/s) gained from a drop height in air of 3.5 feet (1.07 m) above the water surface. The other curves assume a zero initial velocity.

[2] Hoerner, S., Fluid Dynamic Drag, Published by author, New Jersey (1965).

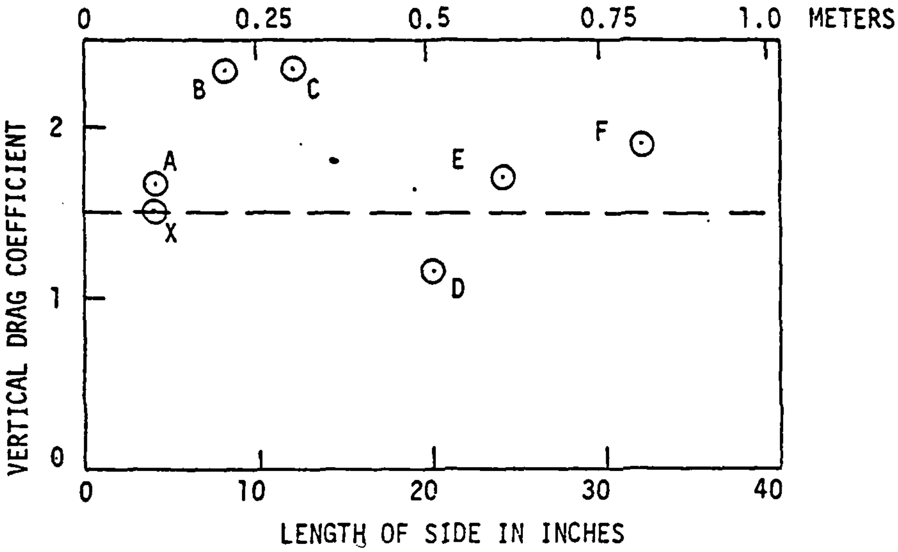


Figure 13a - C_{dv} as a Function of Length of Side

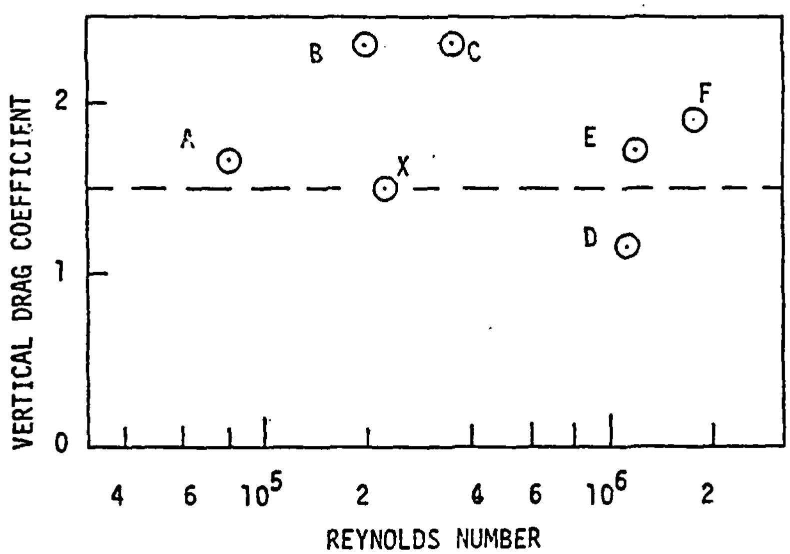


Figure 13b - C_{dv} as a Function of Reynolds Number

Figure 13 - Vertical Drag Coefficient versus Length of Side and Reynolds Number

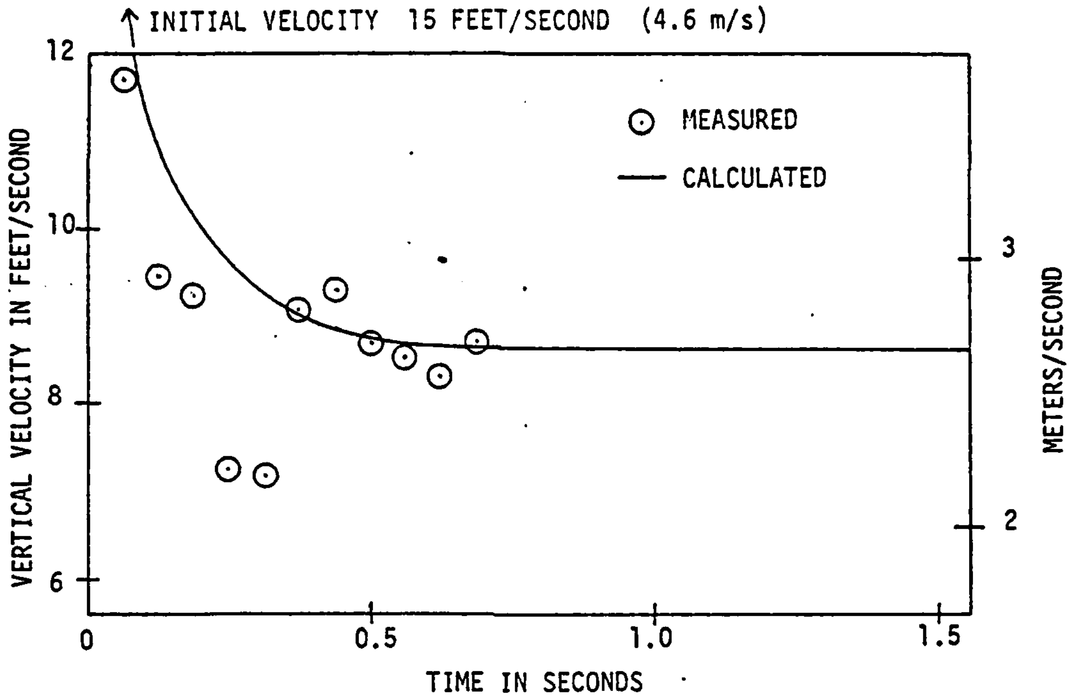


Figure 14 - Velocity - Time Plot for Type X

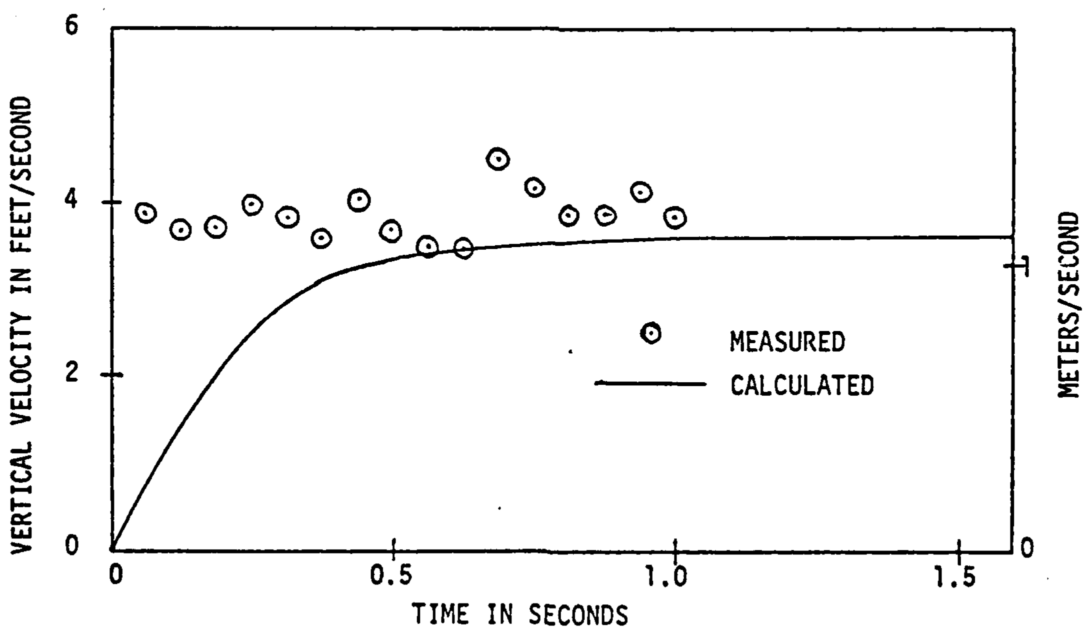


Figure 15 - Velocity - Time Plot for Type B

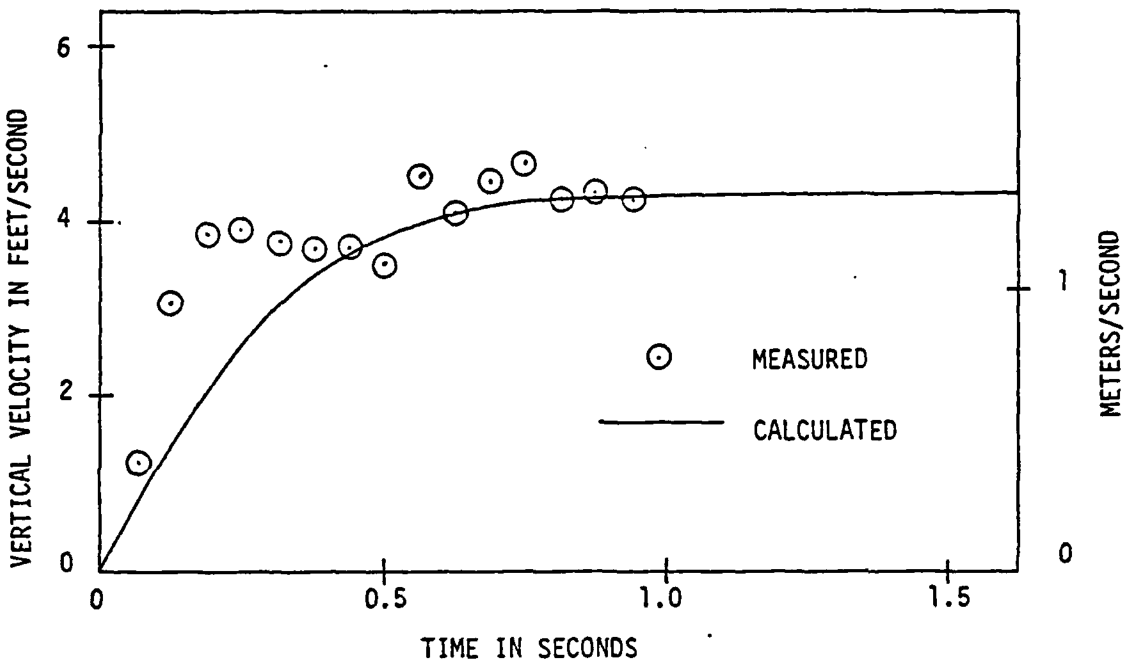


Figure 16 - Velocity - Time Plot for Type C

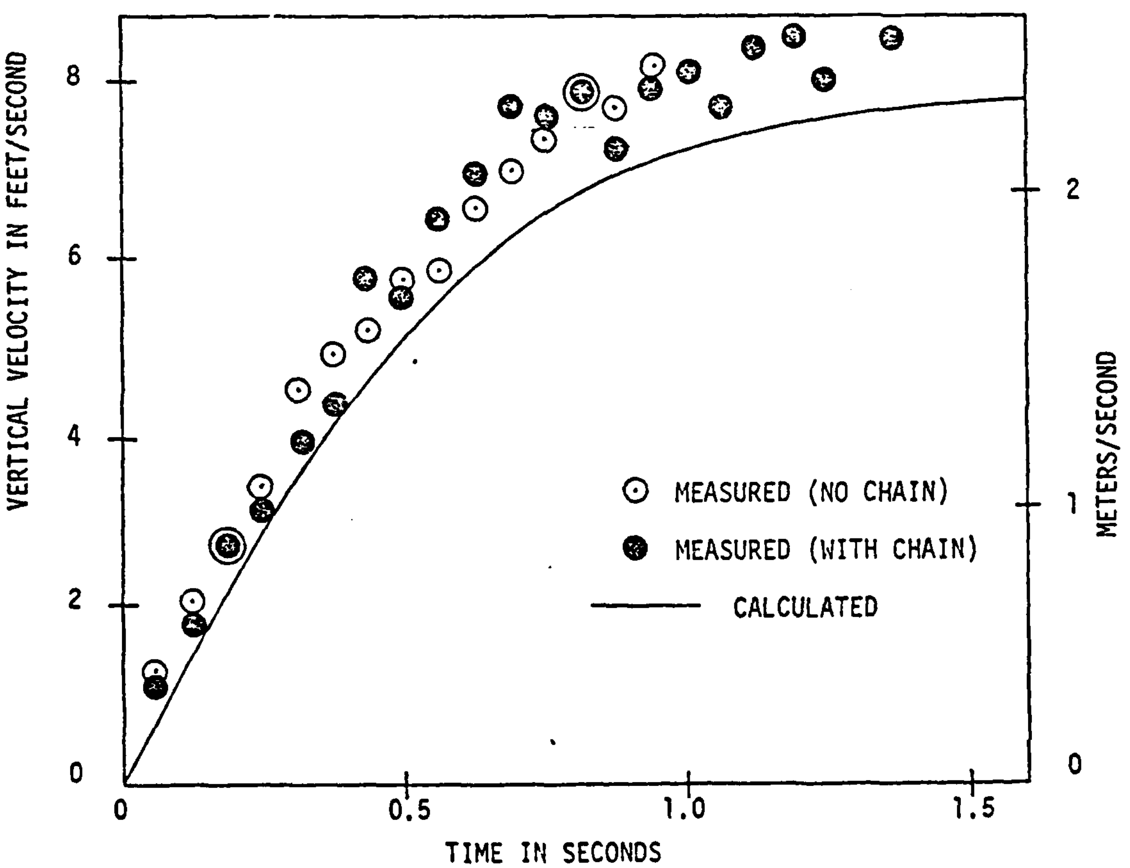


Figure 17 - Velocity-Time Plot for Type D With and Without Chain

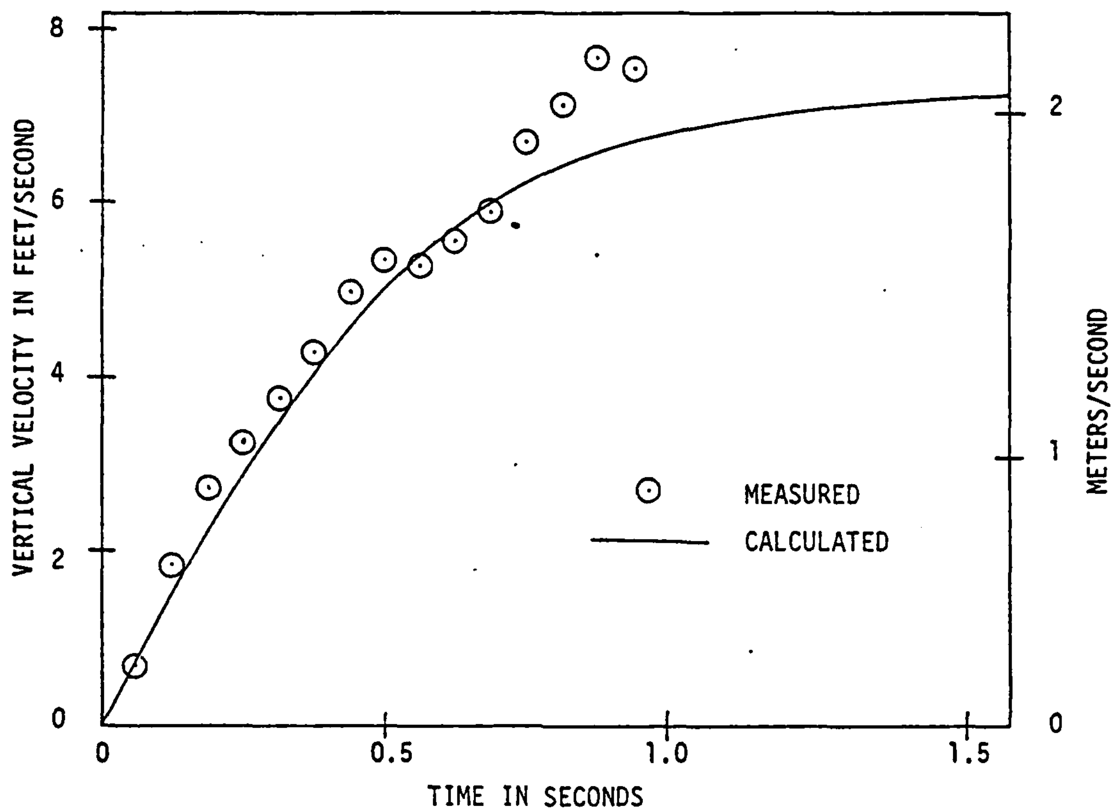


Figure 18 - Velocity-Time Plot for Type E

It can be seen that, except for type B, the calculated values follow the observed values, allowing for experimental data scatter. For type B, some of the sinkers were dropped from a height of about 3.5 feet (1.1 m) into the water, giving an initial velocity to the sinker's motion in the water. It should be noted that the data presented is averaged over five drops and is for the first second or so of drops which lasted for from 8 to 24 seconds. For example, Figure 17 shows that the velocity is higher than the average terminal velocity after 1 second. This is due to the fact that the motion is oscillatory and the velocity drops below the average value a few seconds later. Figure 20 shows a complete record for a drop for type D with chain. The cyclic nature of the vertical velocity can be seen to have a period of about 2 seconds and to have a peak to peak amplitude of about 6 feet per second about a slowly increasing trend.

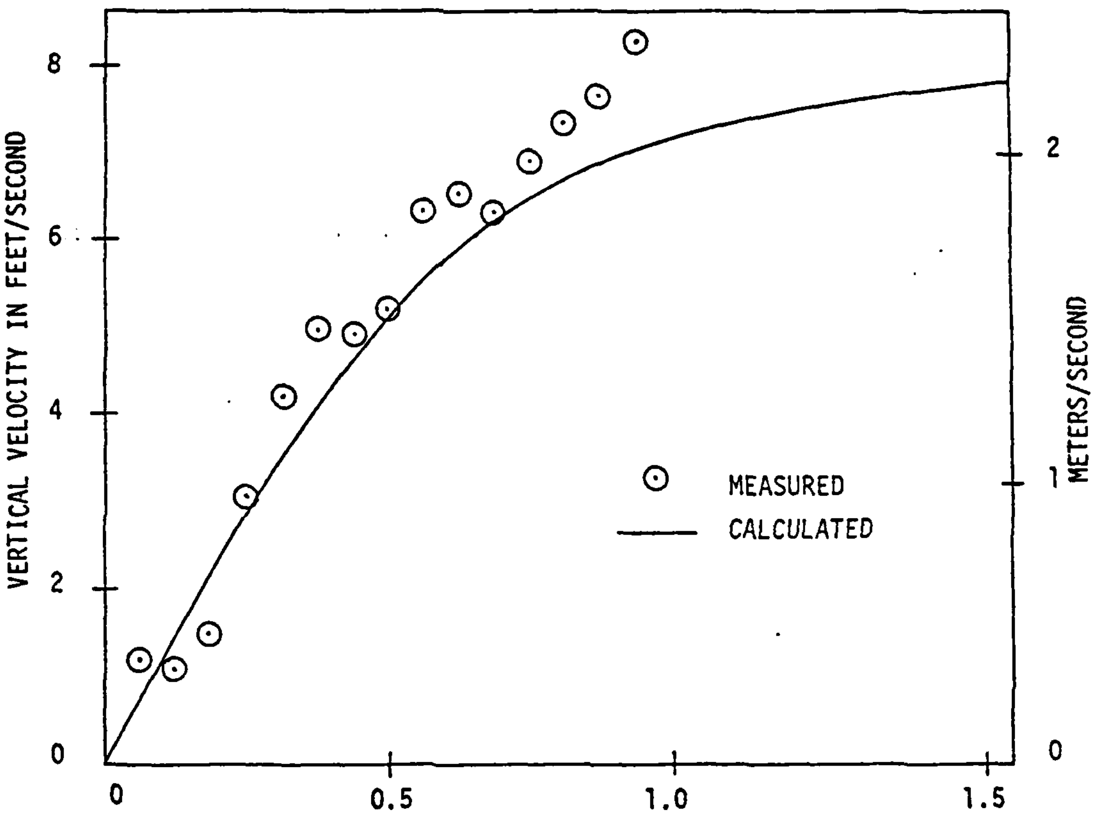


Figure 19 - Velocity-Time Plot for Type F

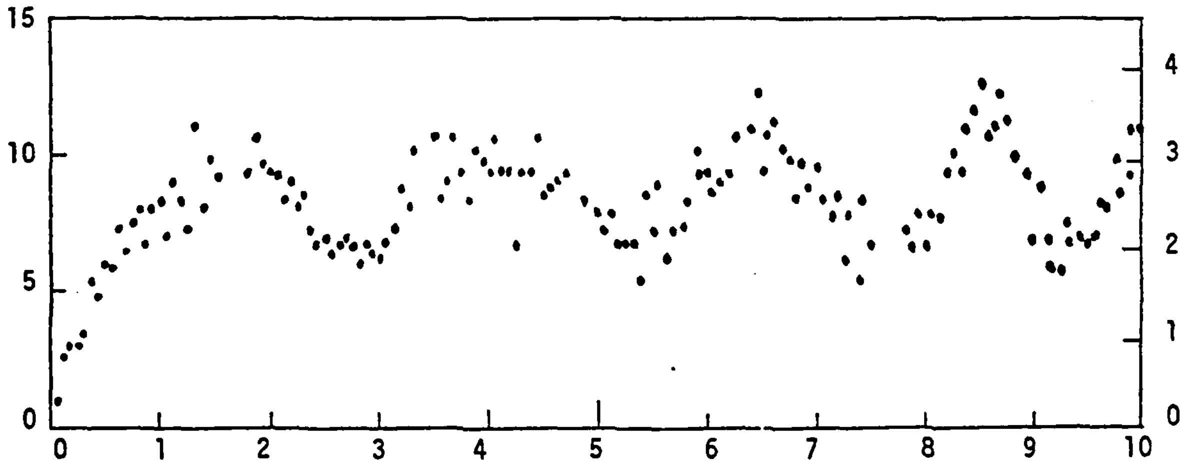


Figure 20 - Complete Velocity - Time Plot for Drop 17 for Sinker Type D

An analysis was made concerning the effects of refraction at the water-air interface in front of the camera and of measuring the vertical velocity from a point on an oscillating sinker. The maximum error in velocity was found to be of the order of 1 percent, well within the measurement error itself. (See Appendix B)

PHASE TWO: CURRENT

To simulate drops into a current two experiments were done. The first was at the Circulating Water Channel (CWC) at DTNSRDC. The drop point was stationary and the current moved past. The second experiment used a moving drop point and a stationary body of water. The results from the CWC are presented first.

The downstream offset is shown in Figure 21, as a function of current speed, for both 4 inch and 8 inch sinkers (Types A and B). Also plotted is the horizontal offset to be expected if the sinkers moved downstream at the speed of the current.

This is found from

$$x = UT$$

where x is the horizontal offset

U is the stream velocity

and T is the experimentally measured time of fall

It can be seen that, for a given stream velocity, the sinkers are carried downstream as if they were convected by the stream. Note that the lighter Type A sinkers are carried farther and have a longer drop time. The corresponding times of descent are shown in Figure 22. The data on which these figures are based are given in Appendix C.

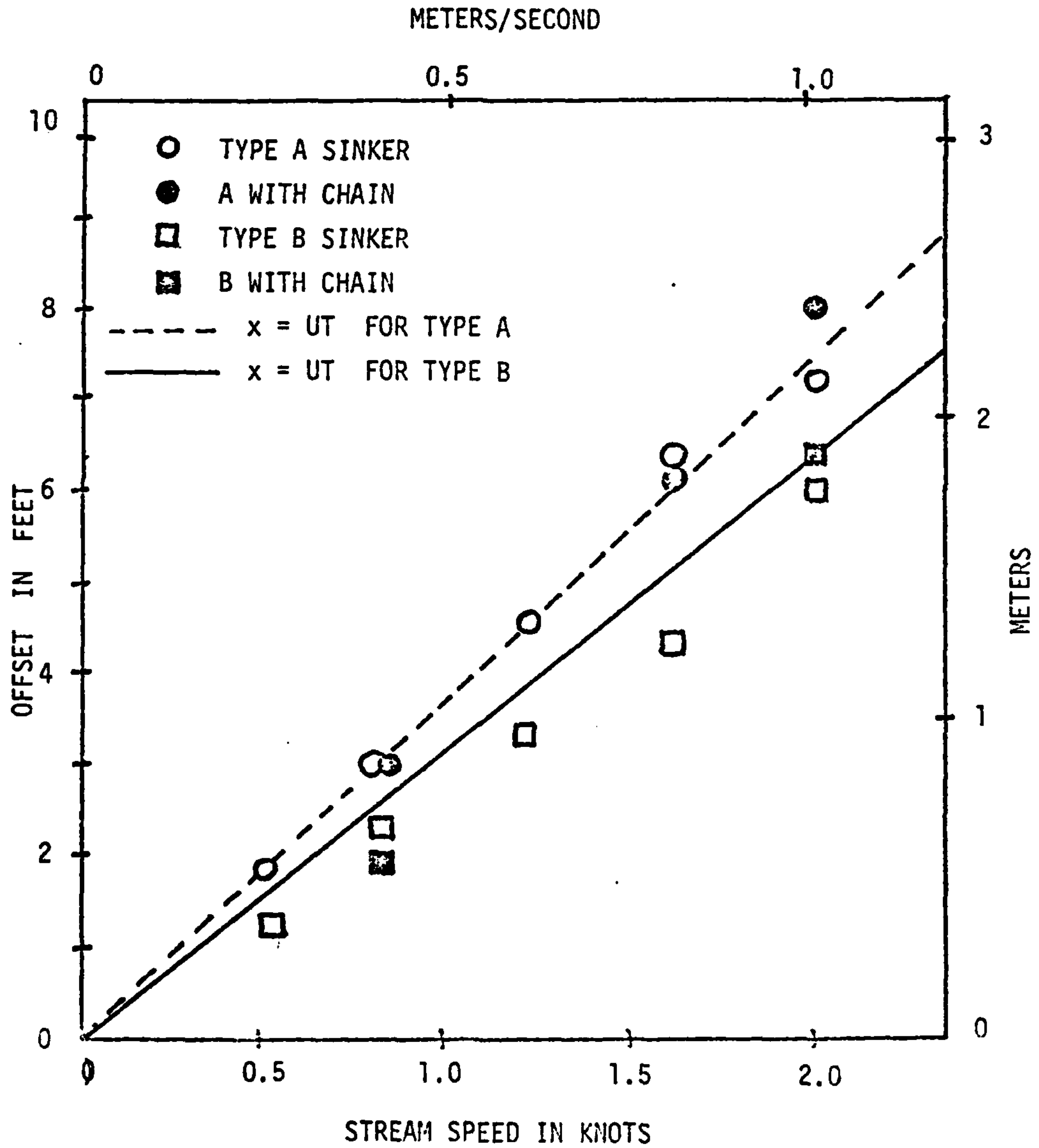


Figure 21 - Average Horizontal Offset as a Function of Stream Speed in the Circulating Water Channel

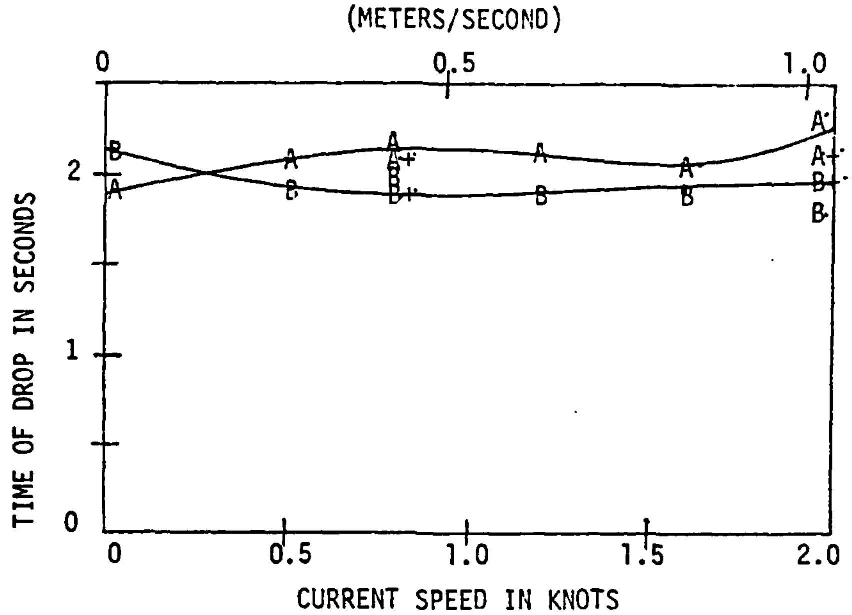


Figure 22 - Time of Descent as a Function of Current

The times of descent are seen to be independent of current speed. This implies that the vertical motion does not depend very much on the horizontal motion. This can be further seen in Figure 22A where the vertical motion of a Type B sinker is shown with and without a current of 2 knots. The path in a current is intertwined with that for still water due to an oscillatory motion that is much stronger in the former case.

The corresponding horizontal motion for the same sinker type is shown in Figure 22B where data for seven drops are shown. The data have little scatter and can be seen to approach and oscillate about a line whose slope is 2 knots, the speed of the water channel. This indicates that, within approximately 0.3 seconds, the sinker reaches the stream velocity and is then convected by it. Equation [6] was used to calculate $\mathcal{K}$, from which a value of C_{dH} = 4.7 was found. This is a very high value and may reflect the tilting of the sinker after release.

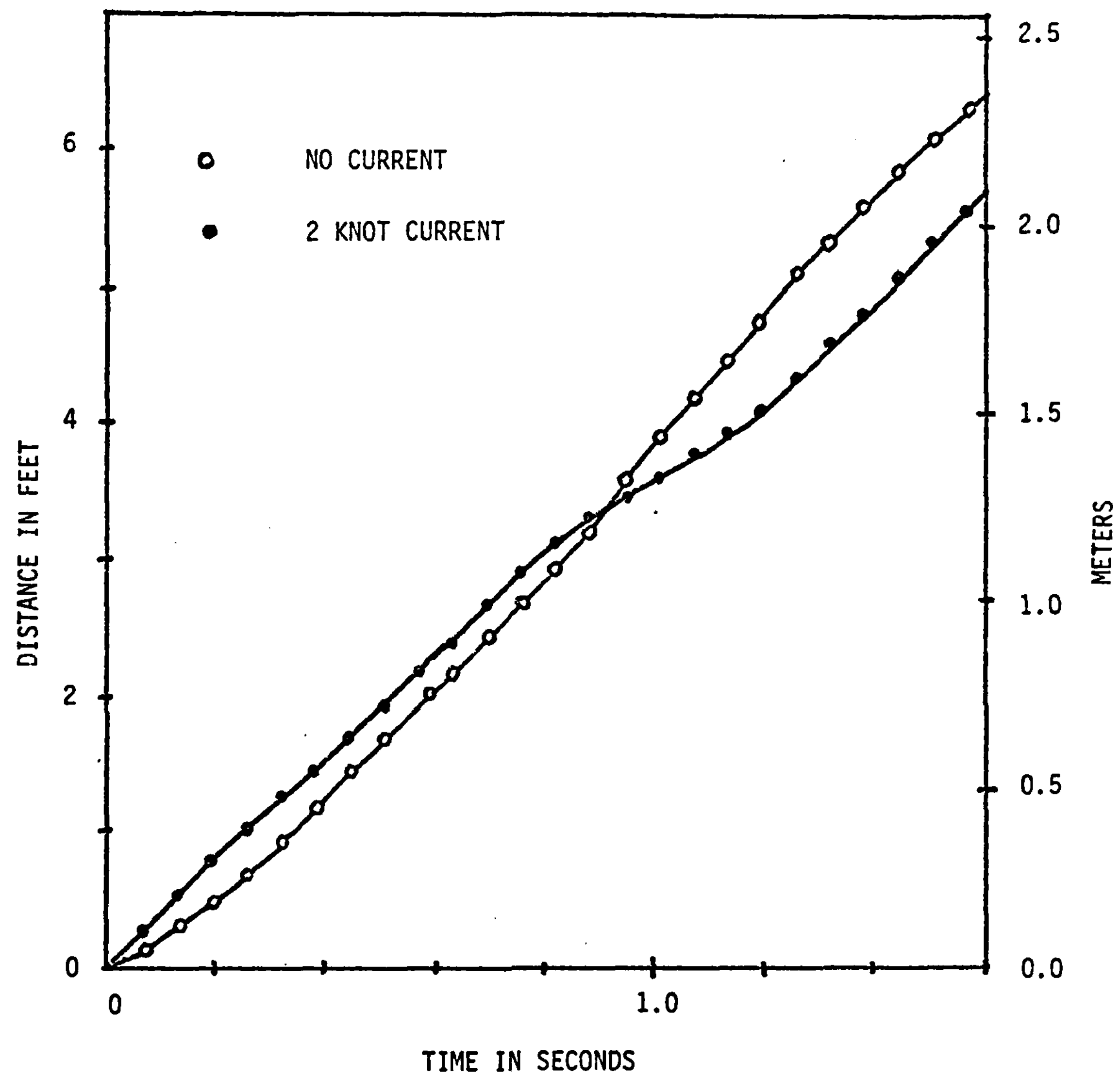


Figure 22A - Vertical Motion of Type B Sinker in Still Water and in a 2 Knot Current

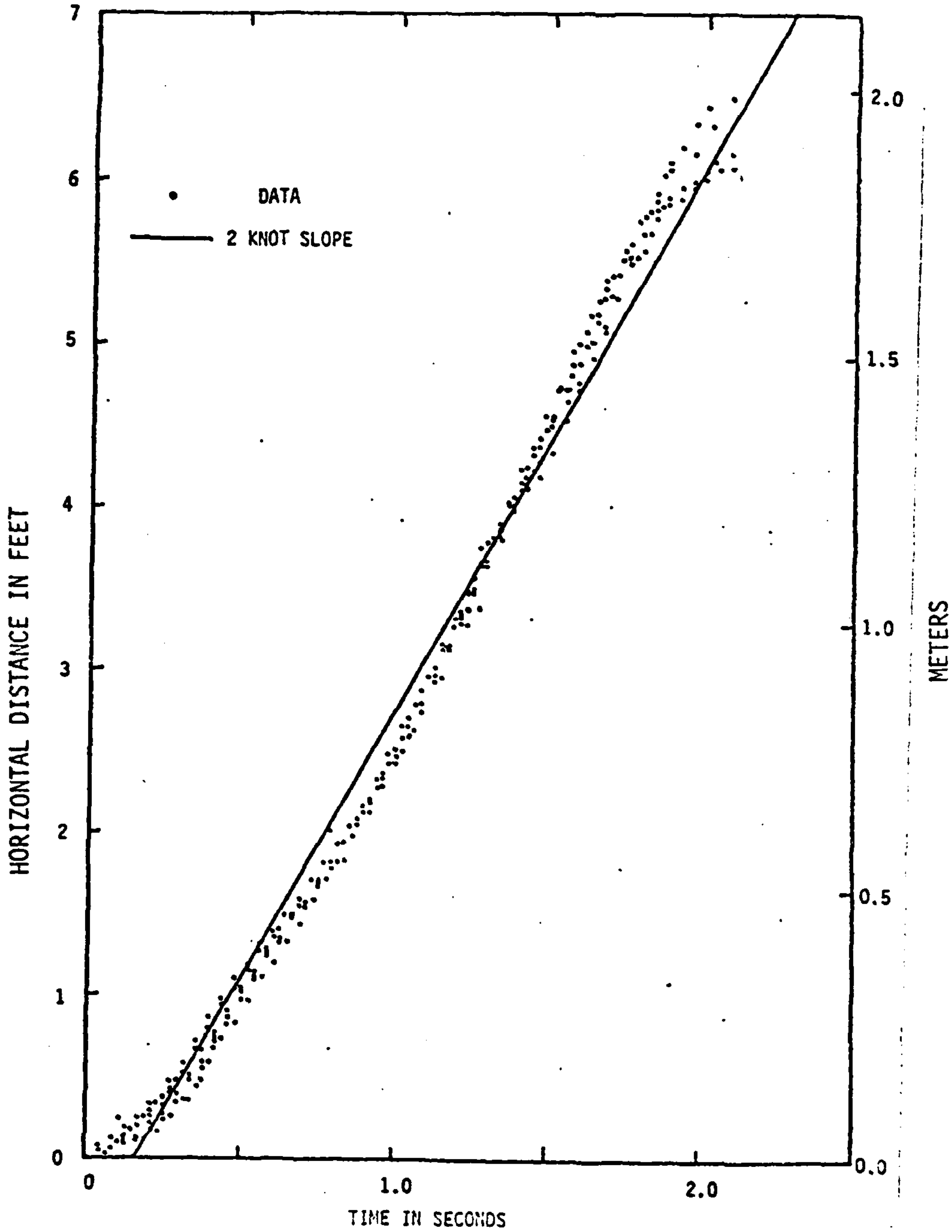
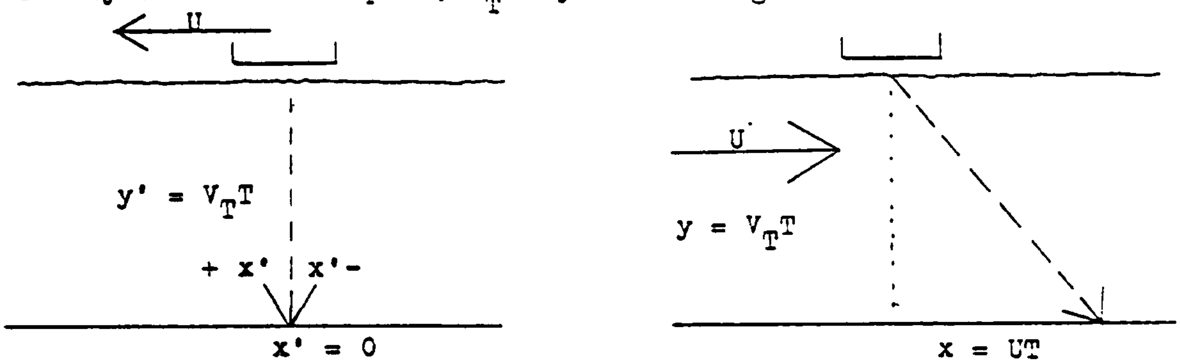


Figure 22B - Horizontal Motion of a Type B Sinker in a 2 Knot Current

DROPS FROM A MOVING CARRIAGE INTO STILL WATER:

The drops into the Circulating Water Channel were from a fixed point into a moving current. The remainder of the drops to be discussed here are those from a moving drop point into still water. By appropriately choosing a frame of reference from which to view the motion, the essential identity of the two approaches can be seen.

Imagine an object being dropped into still water from a carriage moving from right to left at speed U. Suppose the object is small enough to have its horizontal motion instantly retarded and its vertical motion instantly reduced to the terminal velocity. Then, as sketched in Figure 23, as viewed by an observer fixed relative to the towing basin, the object falls vertically at constant speed, V_T say. Now imagine a second observer on the



(a) As Viewed from a Frame Fixed Relative to Basin

(b) As Viewed from a Frame Fixed Relative to Carriage

Figure 23 - Transformation from Fixed to Moving Reference Frame

moving carriage. To his view the object falls vertically at constant speed V_T and moves to the right at constant speed U. In general a simple transformation

$$x = Ut - x'$$
$$y = y'$$

relates the position relative to the carriage, (x,y) to the position relative to the basin, (x', y').

Note that

$$\frac{dx}{dt} = \frac{dx'}{dt} + U \qquad \frac{d^2x}{dt^2} = \frac{d^2x'}{dt^2}$$

$$\frac{dy}{dt} = \frac{dy'}{dt} \qquad \frac{d^2y}{dt^2} = \frac{d^2y'}{dt^2}$$

Thus the velocities may be transformed by simply imposing a left to right uniform velocity U. The accelerations are left unchanged by this Galilean Transformation, and hence the forces acting remain unchanged. The usual statement is that the Newtonian Laws of Motion are invariant under a Galilean Transformation. Thus the two types of experiment used here may be put into correspondence by imposing a constant velocity U.

Table 4 shows the offsets, x', relative to the basin and the offsets, x, relative to the carriage. T is the time of descent, which was 3.0 seconds.

TABLE 4 - OFFSETS FOR D TYPE SINKER FUNCTIONS OF SPEED AT A DEPTH OF 22 FEET (6.7 m)

Speed U		Offset x'		Offset x	
knots	m/s	feet	m	feet	m
0.0	0.00	-1.5 -1.2 -1.0	-0.45 -0.4 -0.3	1.5 1.2 1.0	.45 .4 .3
0.5	0.25	0.8 0.0	0.25 0.0	1.13 2.53	.5 .75
1.0	0.51	1.2 1.5 2.0	0.4 0.45 0.6	3.87 3.57 3.07	1.13 1.08 .93
1.5	0.77	1.2 1.3 2.0	0.4 0.4 0.6	6.4 6.3 5.6	1.91 1.91 1.71
2.0	1.03	0.8 2.0 1.0	0.25 0.6 0.3	9.33 8.13 9.13	2.84 2.49 2.79
Note: T = 3.0 seconds for all cases.					

for all drops measured. The values of x are plotted in Figure 24 as a function of U. Note that x corresponds to the offsets used in the previous sections. The backwards offset at zero speed is probably due

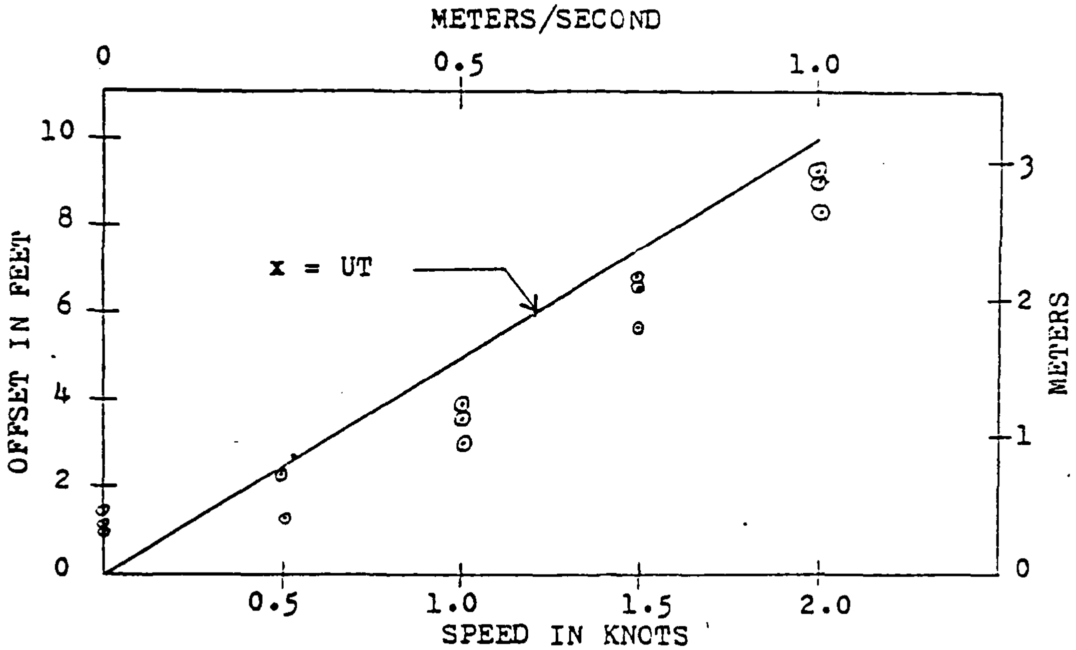


Figure 24 - Horizontal Offset for Type D Sinker in Deep Water Basin

to a slight backwards initial tilt of the sinker, which was always dropped with the same orientation. If this zero offset is subtracted from all of the data then all of the transformed values lie along a line parallel to x = UT, which in a strict interpretation of this transformation principle implies that the sinker took some finite time to reach a horizontal velocity almost equal to the stream velocity. However, since the number of drops is small and the variability of these data over the current range is not sufficient upon which to base any firm conclusions and since the splash into the water of a horizontally moving sinker may be introducing effects not accounted for in the Galilean transformation, further thought and more extensive tests are needed to use this technique for the above stated purpose.

The drop time of 3.0 seconds corresponds to an average velocity of 7.4 feet per second (2.3 m/s) which agrees with the average value obtained from equation (14), with $V_{av} = y/T$.

A further series of 3 drops of a type E sinker was made in 56 feet (17 m) of water at the NSWC 100-foot tank. The horizontal speed was 1 knot (0.51 m/s).

The results are given in Table 5.

TABLE 5 - OFFSETS AT 56 FEET (17 m) FOR 1 KNOT - TYPE E SINKER

Drop	1	2	3
Offset x'	1.2	-1.2	-1.0
Offset x	12.1	14.4	14.3
Note; Time of drop is taken to be 7.9 seconds			

In contrast to the 3 inch (0.08 m) accuracy of the data in Table 4, this data is accurate only to within ±1 foot (0.3 m). The data clearly show, however, that the forward motion $\dot{x}'$ is immediately retarded and that the sinker falls almost vertically. Or as viewed as $\dot{x}$, the sinker is taken up almost immediately by the stream. Calculation of drag coefficients based on the simple theory given previously, gives values from 40 to 90 for C_{dH}. These are clearly nonsensical. The dominant mechanism instead seems to be the loss of momentum to the splash produced on entry into the water.

In summary, the second phase of the investigation shows that the larger sinkers are taken up by the current and fall to the bottom with an offset that differs from U x T by less than the deviation measured from drops into still water of the same depth.

NOTE ON MODELING ;

The sequence of sinker types A through F represents a set of scale models of the full scale sinkers used by the Coast Guard. They do not, however, represent a sequence from which full scale data can be obtained by a scale transformation such as is done for ship powering and resistance. In the present case the effects of gravity and viscosity must be taken into account, since a heavy object is falling in a viscous fluid. Under such conditions, and assuming water to be the fluid, the ratio of weight in water to resistance is preserved only if

$$\frac{L_m^3}{L_p^3} = \frac{\gamma_p - 1}{\gamma_m - 1}$$

where L is the length of the side of the sinker, γ is the specific gravity

of the sinker and the subscripts m and p refer to model and prototype respectively. Thus the largest scale factor allowed by use of even a lead sinker is $L_p/L_m = (10.4/1.4)^{1/3} = 1.95$. Thus a lead sinker of the size of sinker F and weighing 4750 pounds (1050 kg) would allow modeling of a sinker almost twice the size of type F. Practical considerations rule out such an attempt. Therefore the present work is to be regarded as the investigation of a sequence of geometrically and physically similar sinkers and that values for larger sinkers should be estimated by judicious extrapolation from those for smaller sinkers.

CONCLUSIONS

The experiments done with the various sinkers used a 100-foot tank, a circulating water channel and a moving drop into still water. The results for the circulating water channel are for very small sinkers only. It is felt that the very small size is the major reason for the lack of consistency for the results in the CWC compared with those for the other two experiments.

The results for free fall into still water are consistent and valid. Since the full scale sinkers weigh up to 7000 pounds (3200 kg) and above, extrapolation to these higher weights must be made. From the logarithmic plot in Figure 10 and using straight line extrapolation through types D,E and F

$$x = 0.00228\ L^{2.384}$$

for a depth of 88 feet (27 m). For example, the 7000 pound sinker with a length of side of 60 inches (0.15 m)

$$x = 0.00228\ 60^{2.384} = 39.5 \text{ feet}$$

For a type E sinker, from Figure 11b

$$x = 0.11\ y - 1.11 \quad \text{feet}$$

The vertical velocity, for all larger sinkers

$$V_T = 8 \text{ feet/second}$$

The results from drops from the moving carriage into the deep water basin are believed to be accurate. They indicate that, to within an error equivalent to that due to the vertical fluttering motion, the larger sinkers are taken up by the current, giving an offset equal to the product of the current velocity and the time of fall. This time can be reasonably calculated using the terminal velocity instead of the average velocity. The terminal velocity can be calculated using Equation [18] with a drag coefficient of 1. 5. For a sinker falling through a current shear an approximation

$$x = \sum_{i=1}^{N} U_i \frac{y_i}{V_T}$$

can be used where, U is the horizontal velocity in the i-th of the N layers,

y_i is the thickness and V_T is the terminal velocity. However, this is not exact if the shear is abrupt or if the horizontal drag on the cylinder is small. The effects of the latter could best be investigated by drops of large sinkers into an actual shear current of known structure.

APPENDIX A

HORIZONTAL MOTION:

The equation of motion is

$$(m + m_h) \frac{du}{dt} = -\alpha (u-U)\left|u-U\right|$$

with $x = 0$ and $u = U_o$ at $t = 0$

Now suppose $u < U$; the proof is similar for $u > U$

$$\frac{du}{(u-U)^2} = \frac{\alpha}{m} dt$$

$$\frac{1}{u-U} = -\frac{\alpha}{m} t + \text{constant}$$

Use $u = U_o$ at $t = 0$, with some simple manipulation

$$u = \frac{U_o + U\mathcal{K}t}{1 + \mathcal{K}t}$$

$$\mathcal{K} = \frac{\alpha (U - U_o)}{m + m_h}$$

Then

$$x = \int_0^t u \, dt$$

$$= Ut + \frac{1}{\mathcal{K}} (U_o - U) \ln(1 + \mathcal{K}t)$$

VERTICAL MOTION:

The equation of motion is

$$(m + m_v) \frac{dv}{dt} = \beta (V_T^2 - v^2)$$

$$\frac{dv}{V_T^2 - v^2} = \frac{\beta}{m + m_v} dt$$

Use partial fractions and integrate to get

$$\frac{1}{2V_T} \ln\left(\frac{v - V_T}{V_o - V_T}\right)\left(\frac{V_o + V_T}{v + V_T}\right) = \frac{\beta}{m + m_v} t$$

where $v = V_o$ at $t = 0$ has been used. Rewrite after exponentiation

$$\frac{v - V_T}{V_o + V_T} = \frac{V_o - V}{V_o + V} e^{-2\sigma t}$$

where $$\sigma = -\frac{\beta V_T}{m + m_v}$$

Let $$\lambda = \frac{V_T - V_o}{V_T + V_o}$$

and rearrange $$v = V_T \frac{1 - \lambda e^{-2\sigma t}}{1 + \lambda e^{-2\sigma t}}$$

Then $$y = \int_0^t v \, dt$$

$$= V_T t + \frac{V_T}{\sigma} \ln \frac{1 + \lambda^2 e^{-2\sigma t}}{1 + \lambda^2}$$

after a little manipulation and use of integral tables.

Note; $$V_T - v_{av} = V_T - Y/T = -\frac{V_T}{\sigma T} \ln \frac{1 + \lambda^2 e^{-2\sigma t}}{1 + \lambda^2}$$

$$= -\frac{V_T}{\sigma T} \ln \frac{1}{2}$$

for $\lambda = 1$ and $\sigma t \gg 1$

APPENDIX B

During analysis of the movie footage from the NSWC tank, a periodic variation in the vertical velocity was found. One of the possible explanations was the effect of refraction on the apparent velocity of the sinker.

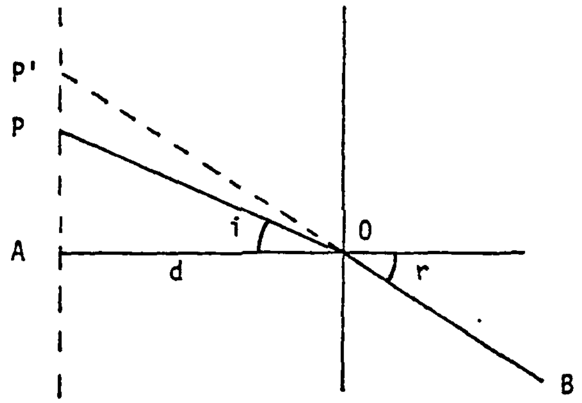


Figure B-1 - Refraction of Light Ray at Water-Air Interface

The sinker position is P on the center line of the tank. A light ray from P strikes the water-glass-air interface, O, and is refracted along OB. The glass window is parallel-sided and can be neglected in the analysis that follows. Due to refraction, the sinker appears to be at P'. The apparent velocity v', is given by

$$v' = \frac{d}{dt} P'A = \frac{dy'}{dt} \tag{B-1}$$

The true velocity v, is given by

$$v = \frac{d}{dt} PA = \frac{dy}{dt} \tag{B-2}$$

The law of refraction gives

$$\sin r = \sin i$$

With $y = d \tan i$ (B-3)

$y^1 = d \tan r$

then

$$\rho = \frac{v'}{\mu v} = \frac{1}{\{1 - (\mu^2 - 1)\eta^2\}^{3/2}} \quad \text{(B-4)}$$

where $\eta \equiv \frac{y}{d} = \tan i$ (B-5)

Note that $\rho = 1$ when $\eta = 0$, i.e. the velocity ratio is adjusted to unity when the sinker is directly opposite the camera. The factor μ, by which the sinker appears nearer the camera is accounted for in the data analysis. Thus ρ is the factor which must be examined to investigate the relationship between actual and apparent vertical velocity.

The results are shown in Figure B-2 for $\mu = 1.35$.

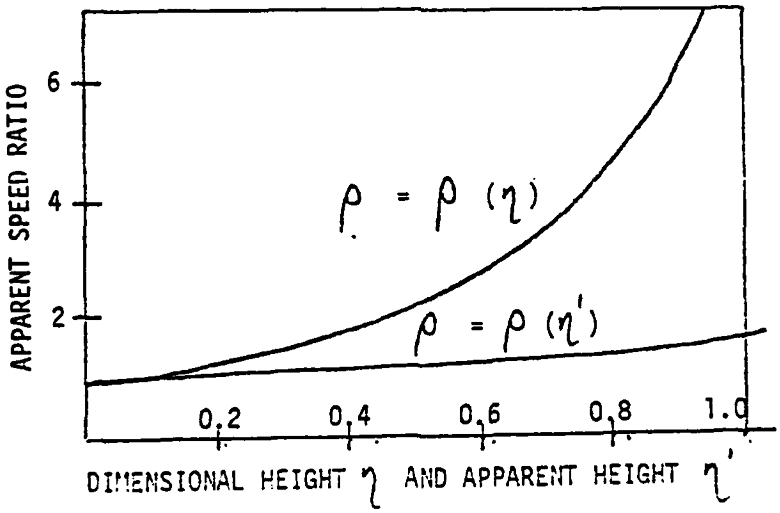


Figure B-2 - Apparent Speed Ratio as a Function of Height and Apparent Height

The field of view used for plotting the vertical velocity corresponded to ± 5.3 feet (±1.4 m) in apparent position. The resultant effect is then

$$\rho_{max} \simeq 1.007$$

Thus the velocity effect due to refraction is less than one percent.

APPENDIX C

TABLE C-1 - DATA FROM DROPS INTO THE 100 FOOT TANK AT THE NAVAL SURFACE WEAPONS CENTER

	Sinker	Depth		Time		Offset		V_T	Remarks
Drop	Type	feet	m	sec		feet	m	ft/sec	
1	D	24	7.3	6.0	C	1.0	0.30	-	Taut Chain
2	D	24	7.3	3.4	C	0.5	0.15	5.7	Chain Slack
3	D	60	18.3	8.0	C	1.0	0.30	5.7	
4	D	88	26.8	11.3	C	3.6	1.10	8.4	
5	D	88	26.8	12.0	C	-	-	7.9	
6	D	88	26.8	10.4	C	4.4	1.34	8.9	
7	D	88	26.8	10.9	C	1.0	0.30	8.5	
8	D	88	26.8	11.3	C	2.1	0.64	8.3	
9	D	88	26.8	11.4	-	1.8	0.55	8.8	
10	D	88	26.8	11.4	-	2.8	0.85	9.2	
11	D	88	26.8	11.4	-	4.1	1.25	8.3	
12	A	88	26.8	29.0	-	-	-	-	
12a	X	88	26.8	10.2	-	-	-	-	
13	D	88	26.8	11.3	-	2.4	0.73	-	
14	D	88	26.8	10.9	C	3.6	1.10	9.0	
15	D	88	26.8	10.6	C	3.1	0.94	8.8	
16	D	88	26.8	11.0	C	2.0	0.91	8.8	
17	D	88	26.8	10.8	C	4.0	1.22	9.4	
18	D	88	26.8	10.7	C	2.0	0.91	9.2	
19	D+D	88	26.8	-	-	0.5	0.15	-	Timer Wrong
20	D+D	88	26.8	-	-	0.5	0.15	-	
20a	B	88	26.8	-	-	-	-	-	
21	D+D	88	26.8	-	-	3.7	1.13	-	
21a	B	88	26.8	-	-	-	-	-	
22	D+D	88	26.8	-	-	4.7	1.43	-	
22a	B	88	26.8	-	-	-	-	-	
23	D+D	88	26.8	10.7	-	-	-	7.6	
23a	B	88	26.8	20.3	-	-	-	-	
24	E	88	26.8	12.2	-	5.8	1.77	8.1	
25	B	88	26.8	27.4	-	1.0	0.30	3.0	Dropped 3.5 ft

TABLE C-1 (cont'd)

Drop	Sinker Type	Depth feet	Depth m	Time sec		Offset feet	Offset m	V_T ft/sec	Remarks
26	B	88	26.8	27.1	-	1.5	0.46	3.5	Dropped from
27a	B	88	26.8	27.3	-	1.6	0.49	-	3.5 ft in Air
27b	B	88	26.8	26.9	-	1.9	0.58	-	"
27c	B	88	26.8	26.6	-	3.0	0.91	-	"
27d	B	88	26.8	27.4	-	3.8	1.16	-	"
27e	B	88	26.8	28.7	-	4.3	1.31	-	"
28	X	88	26.8	10.4	-	0.0	0.00	8.6	
28x	B	88	26.8	21.6	-	-	-	-	
29	E	88	26.8	11.5	-	2.5	0.76	8.0	
30	B	88	26.82	21.7	-	.1.2	0.37	-	
31	B	88	26.8	23.0	-	1.8	0.55	4.2	
31x	B	88	26.8	23.0	-	2.0	0.61	-	
32	E	88	26.8	12.2	-	5.8	1.77	7.9	
33	B	88	26.8	-	-	0.5	0.15	5.2	
34	C	88	26.8	20.8	-	-	-	3.8	
35	C	88	26.8	20.4	-	-	-	4.2	
36	E	88	26.8	12.1	-	7.0	2.13	7.9	
37	C	88	26.8	20.9	-	1.3	0.40	4.4	
37a	C	88	26.8	18.1	-	4.5	1.37	-	Fell Sideways
37b	C	88	26.8	20.1	-	1.6	0.49	-	
38	F	88	26.8	10.9	-	9.0	2.74	8.0	

TABLE C-1 - MEAN AND STANDARD DEVIATION VALUES FOR OFFSETS AND AVERAGE VELOCITIES AT THE 88 FOOT DEPTH

Sinker Type	Size Weight	Offset in feet			Velocity in feet/sec		
		Mean	St Dev	No. Pts	Mean	St Dev	No. Pts
A	4 in	-	-	-	3.0	-	1
B	8 in	1.9	1.2	12	3.59	0.45	13
C	12 in	1.9	1.2	7	4.38	0.25	5
D	250 lb	2.9	1.1	25	8.02	0.33	25
E	500 lb	4.4	2.0	8	7.33	0.26	7
F	1000 lb	8.8	1.7	11	7.93	0.31	10
X	Lead	-	-	-	8.55	0.07	2

TABLE C-2 - MEAN AND STANDARD DEVIATION VALUES FOR OFFSETS AT VARIOUS DEPTHS FOR TYPES E AND F

Sinker Type	Depth Feet	Offset in Feet		
		Mean	Std Dev	No. Pts
E	24	0.93	0.50	4
	40	2.46	1.06	9
	56	3.23	1.89	50
	72	3.08	1.25	9
	88	4.08	1.84	7
	102	4.56	2.27	6
F	24	3.28	1.12	10
	40	3.38	1.29	[illegible]
	56	5.31	1.46	16
	72	7.23	0.73	8
	88	8.85	1.66	11

TABLE C-4 - OFFSETS AND DROP TIMES IN THE CWC

(a) Four Inch Sinker

U		x		T
knots	m/s	feet	m	sec
0.5	0.26	1.8	0.39	2.10
0.8	0.41	3.1	0.65	2.18
1.2	0.62	4.6	0.98	2.14
1.6	0.82	6.4	1.30	2.10
2.0	1.03	7.6	1.89	2.30

(b) Eight Inch Sinkers

U		x		T
knots	m/s	feet	m	sec
0.5	0.26	1.28	0.55	1.98
0.8	0.41	2.13	0.94	1.98
1.2	0.62	3.23	1.39	1.92
1.6	0.82	4.25	1.95	1.94
2.0	1.03	6.21	2.33	1.90

APPENDIX B

TEST DATA

$\bar{O}$ = Average of Offset S_o = Standard Deviation of the Offset S_o^2 = Variance of the Offset $\bar{T}$ = Average of the Descent Time

S_t = Standard Deviation of the Descent Time S_t^2 = Variance of the Descent Time σ^2 = Circular Normal Variance of Offset = $\frac{\bar{O}^2 + S_o^2\left(\frac{n-1}{n}\right)}{2}$

TEST DATA SERIES A

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)	HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)	DESCENT TIME (sec)	CLOCK AND DATE
N	250	4	24	NO	0	0	1.54	0500	3.23	02/28
AA	250	4	24	NO	0	270	2.30	0700	-	02/28
AE	250	4	24	NO	0	270	1.31	0630	3.12	03/01
BP	250	4	24	NO	0	90	2.07	0630	3.16	1748-03/01
BI	250	4	24	NO	0	90	0.95	0800	3.32	1545-03/01
						$\bar{O}$ =	1.63	$\bar{T}$ =	3.21	
						S_o =	0.55	S_t =	0.088	
						S_o^2 =	0.30	S_t^2 =	0.008	
						σ^2 =	1.46			
M	1000	5	24	YES	0	0	4.49	0330	-	02/28
AF	1000	5	24	YES	0	270	3.77	0230	3.27	1409-03/01
AH	1000	5	24	YES	0	180	4.95	0630	-	1425-03/01
AN	1000	5	24	YES	0	270	4.27	0200	3.51	1508-03/01
AP	1000	5	24	YES	0	175	3.61 II	0300	3.46	1522-03/01
						$\bar{O}$ =	4.22	$\bar{T}$ =	3.41	
						S_o =	0.54	S_t =	0.127	
						S_o^2 =	0.30	S_t^2 =	0.016	
						σ^2 =	9.01			
I	250	4	88	YES	0	0	1.02	0600	11.37	02/28
E	250	4	88	YES	0	270	4.66	1000	11.34	1516-03/04
W	250	4	88	YES	0	90	1.80	0400	-	1411-03/04
AU	250	4	88	YES	0	270	4.13	0830	11.24	1558-03/01
BM	250	4	88	YES	0	90	3.61II	0800	10.70	1750-03/01
						$\bar{O}$ =	3.04	$\bar{T}$ =	11.16	
						S_o =	1.56	S_t =	0.313	
						S_o^2 =	2.44	S_t^2 =	0.098	
						σ^2 =	5.61			

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)	HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)	DESCENT TIME (sec)	CLOCK AND DATE
H	1000	5	88	NO	0	0	10.14	0330	11.53	02/28
R	1000	5	88	NO	0	180	10.33	0330	11.37	1406-03/04
AG	1000	5	88	NO	0	270	11.52	0200	11.65	02/28
AK	1000	5	88	NO	0	270	7.55	1000	11.30	1332-03/01
BJ	1000	5	88	NO	0	270	10.42	0400	11.08	1555-03/01
						$\bar{O}$ =	9.99	$\bar{T}$ =	11.39	
						S_o =	1.47	S_t =	0.219	
						S_o^2 =	2.15	S_t^2 =	0.048	
						σ^2 =	50.78			
I	250	4	24	YES	6	0	0.82	1000	3.39	02/28
P	250	4	24	YES	6	90	1.64	1030	3.46	1533-03/04
BH	250	4	24	YES	6	0	1.87	1000	3.25	1703 03/01
AB	250	4	24	YES	6	270	2.30	0100	3.45	03/01
AM	250	4	24	YES	6	180	0.66	0530	3.92	1456-03/01
						$\bar{O}$ =	1.46	$\bar{T}$ =	3.49	
						S_o =	0.70	S_t =	0.252	
						S_o^2 =	0.49	S_t^2 =	0.064	
						σ^2 =	1.26			
K	1000	5	24	NO	6	180	1.35	-	3.69	02/28
U	1000	5	24	NO	6	180	2.69	0200	3.79	1505-03/04
V	1000	5	24	NO	6	180	2.40	0100	-	02/28
AW	1000	5	24	NO	6	270	2.49	0400	3.62	1452-03/01
BI	1000	5	24	NO	6	270	2.82	0400	3.92	1646-03/01
						$\bar{O}$ =	2.35	$\bar{T}$ =	3.76	
						S_o =	0.58	S_t =	0.130	
						S_o^2 =	0.34	S_t^2 =	0.017	
						σ^2 =	2.90			
C	250	4	88	NO	6	270	0.85	0430	11.58	1426-03/04
D	250	4	88	NO	6	90	2.82	0700	11.11	1440-03/04
Z	250	4	88	NO	6	180	4.46	0830	11.15	02/28
AR	250	4	88	NO	6	270	2.53	1100	10.90	02/28
BS	250	4	88	NO	6	80	3.61	0800	11.07	1518-03/01
						$\bar{O}$ =	2.85	$\bar{T}$ =	11.16	
						S_o =	1.35	S_t =	0.252	
						S_o^2 =	1.82	S_t^2 =	0.064	
						σ^2 =	4.79			

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)	HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)	DESCENT TIME (sec)	CLOCK AND DATE
G	1000	5	88	YES	6	0	7.17	0300	11.01	1428-03/04
S	1000	5	88	YES	6	0	6.00	0300	-	02/28
AD	1000	5	88	YES	6	180	7.84	0230	-	02/28
BC	1000	5	88	YES	6	270	9.08	0100	11.15	1626-03/01
BR	1000	5	88	YES	6	90	8.33	0200	11.47	1658-03/04
						$\bar{O}$ =	7.68	$\bar{T}$ =	11.21	
						S_o =	1.17	S_t =	0.236	
						S_o^2 =	1.37	S_t^2 =	0.056	
						σ^2 =	10.07			

TEST DATA SERIES B

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)	HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)	DESCENT TIME (sec)	CLOCK AND DATE
AY	250	4	56	NO	0	90	3.64	0800	7.11	1438-03/01
BN	250	4	56	YES	0	270	4.27	0930	7.61	1547-03/04
						$\bar{O}$ =	3.95	$\bar{T}$ =	7.36	
						S_o =	0.44	S_t =	0.354	
						S_o^2 =	0.19	S_t^2 =	0.125	
						σ^2 =	7.85			
BK	250	4	56	NO	6	90	3.25	0830	7.26	1608-03/01
BG	250	4	56	YES	6	90	1.948	0500	7.21	1352-03/01
						$\bar{O}$ =	2.59	$\bar{T}$ =	7.24	
						S_o =	0.93	S_t =	0.040	
						S_o^2 =	0.86	S_t^2 =	0.001	
						σ^2 =	3.58			
AZ	1000	5	56	NO	0	270	5.18	0300	7.42	1436-03/01
BO	1000	5	56	YES	0	0	4.04	0630	7.38	1729-03/01
						$\bar{O}$ =	4.61	$\bar{T}$ =	7.40	
						S_o =	0.81	S_t =	0.028	
						S_o^2 =	0.66	S_t^2 =	0.001	
						σ^2 =	10.79			

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)		HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)		DESCENT TIME (sec)	CLOCK AND DATE
BB	1000	5	56	NO	6	270		4.82	0400		7.57	1533-03/01
BE	1000	5	56	YES	6	180		5.09	0230		7.61	1637-03/01
						$\bar{O}$	=	4.95	$\bar{T}$	=	7.59	
						S_o	=	0.19	S_t	=	0.028	
						S_o^2	=	0.03	S_t^2	=	0.001	
						$_o^2$	=	12.30				
AL	500	6	24	NO	0	90		0.20	0900		3.69	1346-03/01
AS	500	6	24	YES	0	0		1.288	0230		3.97	1547-03/01
						$\bar{O}$	=	0.74	$\bar{T}$	=	3.83	
						S_o	=	0.77	S_t	=	0.198	
						S_o^2	=	0.58	S_t^2	=	0.039	
						$_o^2$	=	0.42				
BA	500	6	24	NO	6	180		1.05	0700		3.63	1504-03/01
BQ	500	6	24	YES	6	0		1.18	1200		3.67	1751-03/01
						$\bar{O}$	=	1.12	$\bar{T}$	=	3.65	
						S_o	=	0.09	S_t	=	0.028	
						S_o^2	=	0.01	S_t^2	=	0.001	
						$_o^2$	=	0.63				
AV	500	6	88	NO	0	270		6.20	0230		12.40	1420-03/01
BI	500	6	88	YES	0	0		2.49	1000		-	1722-03/04
						$\bar{O}$	=	4.35	$\bar{T}$	=	12.40	
						S_o	=	2.62	S_t	=	-	
						S_o^2	=	6.88	S_t^2	=	-	
						$_o^2$	=	11.16				
BD	500	6	88	NO	6	180		3.67	0800		12.93	1516-03/01
BF	500	6	88	YES	6	90		2.008	0800		12.04	1649-03/01
						$\bar{O}$	=	2.84	$\bar{T}$	=	12.49	
						S_o	=	1.18	S_t	=	0.630	
						S_o^2	=	1.39	S_t^2	=	0.400	
						$_o^2$	=	4.37				

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)	HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)	DESCENT TIME (sec.)	CLOCK AND DATE
O	500	2	56	NO	0	0	1.74	0200	7.31	02/28
Y	500	2	56	NO	0	180	1.51	0530	7.50	02/28
AU	500	6	56	NO	0	90	2.26	0130	8.10	1406-03/01
BU	500	6	56	NO	0	100	2.99	0200	7.91	1621-03/01
A	500	6	56	NO	0	0	3.58	0200	7.90	1403-03/04
B	500	6	56	YES	0	0	3.94	0100	8.17	1456-03/04
I	500	2	56	YES	0	180	6.00	1030	7.17	02/28
AL	500	2	56	YES	0	270	1.87	0230	7.24	02/28
AT	500	6	56	YES	0	180	3.22	0400	7.64	1536-03/01
BV	500	6	56	YES	0	0	3.58	1200	8.07	1750-03/04
						$\bar{O}$ =	3.07	$\bar{t}$ =	7.70	
						S_o =	1.34	S_t =	0.379	
						S_o^2 =	1.80	S_t^2 =	0.143	
						σ^2 =	5.52			
F	500	2	56	NO	6	0	1.35	0200	7.71	02/28
Q	500	2	56	NO	6	180	2.20	0700	7.60	02/28
AI	500	6	56	NO	6	270	0.26	1000	8.15	03/01
AQ	500	6	56	NO	6	90	1.84	1130	7.67	1335-03/01
BW	500	6	56	NO	6	90	2.30	1000	8.06	1633-03/01
X	500	2	56	YES	6	270	2.72	1030	7.76	02/28
AJ	500	6	56	YES	6	180	2.79	0730	8.06	1443-03/01
AX	500	6	56	YES	6	0	1.62	0430	8.03	1612-03/01
J	500	6	56	YES	6	0	2.07	1000	-	1444-03/04
BX	500	6	56	YES	6	90	0.208	0900	8.17	1730-03/04
						$\bar{O}$ =	1.74	$\bar{t}$ =	7.91	
						S_o =	0.91	S_t =	0.224	
						S_o^2 =	0.83	S_t^2 =	0.050	
						σ^2 =	1.88			
CB	500	6	56	NO	3	180	2.23	0700	7.69	1659-03/01
CD	500	6	56	NO	3	270	2.95	0200	8.02	1712-03/01
CF	500	6	56	NO	3	0	4.04	1230	7.79	1727-03/01
CH	500	6	56	NO	3	90	2.36	0800	8.14	1738-03/01
F3*	500	6	56	NO	3	90	3.67	1230	8.31	0957-03/05
F4*	500	2	56	NO	3	0	1.25	0500	-	1048-03/05
CA	500	6	56	YES	3	180	2.95	1000	7.85	1800-03/04
CG	500	6	56	YES	3	0	1.84	0200	8.30	1618-03/04
CC	500	6	56	YES	3	90	2.33	0530	-	1627-03/04
CE	500	6	56	YES	3	270	3.31	0100	8.07	1638-03/04
						$\bar{O}$ =	2.69	$\bar{t}$ =	8.06	
						S_o =	0.85	S_t =	0.191	
						S_o^2 =	0.73	S_t^2 =	0.036	
						σ^2 =	3.95			

*Duplicated in TEST DATA SERIES D

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)	HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)	DESCENT TIME (sec.)	CLOCK AND DATE
TEST DATA SERIES C										
D1	500	6	40	NO	1.5	0	2.76	0100	6.04	1530-03/04
D2	500	6	40	NO	1.5	90	4.048	1100	5.89	1813-03/04
D3	500	6	40	NO	1.5	270	3.05	0230	5.92	0850-03/05
D4	500	6	40	NO	1.5	170	3.38	0200	6.36	0939-03/05
						$\bar{o}$ =	3.31	$\bar{t}$ =	6.05	
						S_o =	0.55	S_t =	0.215	
						S_o^2 =	0.30	S_t^2 =	0.046	
						σ^2 =	5.58			
D5	1000	5	40	YES	1.5	270	2.95	0300	5.58	1601-03/04
D6	1000	5	40	YES	1.5	0	2.08	0430	-	1732-03/04
D7	1000	5	40	YES	1.5	90	3.41	0200	5.95	1828-03/04
D8	1000	5	40	YES	1.5	180	5.05	0230	-	0847-04/05
						$\bar{o}$ =	3.37	$\bar{t}$ =	5.77	
						S_o =	1.25	S_t =	0.262	
						S_o^2 =	1.56	S_t^2 =	0.068	
						σ^2 =	6.27			
D9	500	1	72	YES	1.5	90	3.12	0800	-	1544-03/04
D10	500	1	72	YES	1.5	270	2.30	0300	10.26	1653-03/04
D11	500	2	72	YES	1.5	180	1.648	0230	9.60	1839-03/04
D12	500	2	72	YES	1.5	0	2.07	0200	9.71	0915-03/05
						$\bar{o}$ =	2.28	$\bar{t}$ =	9.86	
						S_o =	0.62	S_t =	0.354	
						S_o^2 =	0.39	S_t^2 =	0.125	
						σ^2 =	2.75			
D13	1000	5	72	NO	1.5	180	7.92	0230	9.54	1512-03/04
D14	1000	5	72	NO	1.5	270	7.46	0230	9.10	1229-03/05
D15	1000	5	72	NO	1.5	0	7.58	0200	9.20	0911-03/05
D16	1000	5	72	NO	1.5	90	7.50	0330	9.45	1016-03/05
						$\bar{o}$ =	7.61	$\bar{t}$ =	9.32	
						S_o =	0.21	S_t =	0.207	
						S_o^2 =	0.04	S_t^2 =	0.043	
						σ^2 =	29.01			

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)	HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)	DESCENT TIME (sec)	CLOCK AND DATE
D17	500	1	40	YES	4.5	270	2.46	0200	6.01	1818-03/04
D18	500	1	40	YES	4.5	90	1.25	0500	5.86	1832-03/04
D19	500	1	40	YES	4.5	0	2.69	0530	6.15	0852-03/05
D20	500	2	40	YES	4.5	180	0.62	0200	5.71	0917-03/05
						$\bar{O}$ =	1.76	$\bar{T}$ =	5.93	
						S_o =	0.99	S_t =	0.190	
						S_o^2 =	0.97	S_t^2 =	0.036	
						σ^2 =	1.90			
D21	1000	5	40	NO	4.5	270	4.76	0230	5.67	1623-03/04
D22	1000	5	40	NO	4.5	90	1.94	0600	-	1746-03/04
D23	1000	5	40	NO	4.5	0	1.48	0300	-	1811-03/04
D24	1000	5	40	NO	4.5	180	4.33	0300	5.56	0933-03/05
						$\bar{O}$ =	3.13	$\bar{T}$ =	5.62	
						S_o =	1.66	S_t =	0.078	
						S_o^2 =	2.75	S_t^2 =	0.006	
						σ^2 =	5.92			
D25	500	6	72	NO	4.5	0	2.62	1030	10.40	1542-03/04
D26	500	6	72	NO	4.5	90	2.76	0330	10.48	1645-03/04
D27	500	6	72	NO	4.5	270	4.56	0100	10.59	1835-03/04
D28	500	1	72	NO	4.5	180	5.58	0630	10.05	0943-03/05
F13	500	6	72	NO	4.5	270	3.08	1000	10.57	1020-03/05
						$\bar{O}$ =	3.72	$\bar{T}$ =	10.42	
						S_o =	1.29	S_t =	0.219	
						S_o^2 =	1.68	S_t^2 =	0.048	
						σ^2 =	7.59			
D29	1000	5	72	YES	4.5	270	5.91	0400	9.36	1718-03/04
D30	1000	5	72	YES	4.5	180	7.50	0400	9.10	1238-03/05
D31	1000	5	72	YES	4.5	90	7.75	1200	9.41	1040-03/05
D32	1000	5	72	YES	4.5	0	6.27	0300	-	1126-03/05
						$\bar{O}$ =	6.86	$\bar{T}$ =	9.29	
						S_o =	0.91	S_t =	0.166	
						S_o^2 =	0.82	S_t^2 =	0.028	
						σ^2 =	23.82			

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)	HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)	DESCENT TIME (sec)	CLOCK AND DATE
TEST DATA SERIES D										
E1	1000	5	56	YES	3	270	6.20	0330	7.49	1635-03/04
E2	1000	5	56	YES	3	90	4.43	0400	7.30	1252-03/05
E3	1000	5	56	NO	3	0	5.91	0300	7.72	1758-03/04
E4	1000	5	56	NO	3	180	6.62	0230	-	1330-03/05
						$\bar{O}$ =	5.79	$\bar{T}$ =	7.50	
						S_o =	0.95	S_t =	0.210	
						S_o^2 =	0.91	S_t^2 =	0.044	
						σ^2 =	17.10			
E5	1000	5	56	YES	4.5	0	3.97	0430	-	1146-03/05
E6	1000	5	56	YES	4.5	180	1.97	0200	-	1301-03/05
E7	1000	5	56	NO	4.5	0	6.56	0300	7.44	1102-03/05
E8	1000	5	56	NO	4.5	180	7.42	0330	-	1315-03/05
						$\bar{O}$ =	4.98	$\bar{T}$ =	7.44	
						S_o =	2.49	S_t =	-	
						S_o^2 =	6.20	S_t^2 =	-	
						σ^2 =	14.72			
E9	1000	5	56	YES	1.5	180	7.33	0330	7.30	1244-03/05
E10	1000	5	56	YES	1.5	0	6.20	0330	7.20	1210-03/05
E11	1000	5	56	NO	1.5	90	5.67	0400	7.40	1310-03/05
E12	1000	5	56	NO	1.5	270	3.81	0300	7.33	0954-03/05
						$\bar{O}$ =	5.75	$\bar{T}$ =	7.31	
						S_o =	1.47	S_t =	0.083	
						S_o^2 =	2.16	S_t^2 =	0.007	
						σ^2 =	17.35			
F1	500	2	56	YES	3	180	4.108	0500	7.94	0855-03/05
F2	500	1	56	YES	3	0	4.56	0330	8.17	1023-03/05
F3	500	6	56	NO	3	90	3.67	1230	8.31	0957-03/05
F4	500	2	56	NO	3	0	1.25	0500	-	1048-03/05
						$\bar{O}$ =	3.40	$\bar{T}$ =	8.14	
						S_o =	1.48	S_t =	0.187	
						S_o^2 =	2.18	S_t^2 =	0.035	
						σ^2 =	6.58			

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)	HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)	DESCENT TIME (sec)	CLOCK AND DATE
F5	500	1	56	YES	4.5	0	2.99H	0400	8.09	0921-03/05
F6	500	2	56	YES	4.5	90	1.15	0530	7.72	1000-03/05
F7	500	6	56	NO	4.5	270	3.35	1230	-	1212-03/05
F8	500	1	56	NO	4.5	0	4.40	0600	7.95	1004-03/05
						$\bar{O}$ =	2.97	$\bar{T}$ =	7.92	
						S_o =	1.35	S_t =	0.187	
						S_o^2 =	1.83	S_t^2 =	0.035	
						σ^2 =	5.19			
F9	500	2	56	YES	1.5	270	2.69H	0300	7.55	1025-03/05
F10	500	1	56	YES	1.5	90	5.02	0230	7.88	1045-03/05
F11	500	6	56	NO	1.5	180	3.08H	1230	8.06	1050-03/05
F12	500	6	56	NO	1.5	0	3.87	1230	8.05	0918-03/05
						$\bar{O}$ =	3.67	$\bar{T}$ =	7.89	
						S_o =	1.03	S_t =	0.238	
						S_o^2 =	1.06	S_t^2 =	0.057	
						σ^2 =	7.11			

TEST DATA SERIES E

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	WITH CHAIN YES OR NO	VERTICAL HEIGHT (ft)	ORIENTATION (degrees)	HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (clock)	DESCENT TIME (sec)	CLOCK AND DATE
G1	500	1	102	NO	3	0	7.50	0400	13.90	1214-03/05
G2	500	2	102	NO	3	270	5.48	0230	13.68	1111-03/05
G3	500	6	102	NO	3	90	4.86H	1000	-	1134-03/05
G4	500	1	102	NO	3	180	5.81	0530	13.98	1132-03/05
G5	500	2	102	NO	3	90	2.23	0900	14.10	1216-03/05
G6	500	2	102	NO	3	270	1.51	0800	13.56	1130-03/05
						$\bar{O}$ =	4.56	$\bar{T}$ =	13.84	
						S_o =	2.27	S_t =	0.221	
						S_o^2 =	5.17	S_t^2 =	0.049	
						σ^2 =	12.58			

TEST CODE	NOMINAL SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	NO CHAIN POSITION ENTERING WATER	VERTICAL HEIGHT (ft)		HORIZONTAL OFFSET (ft)	OFFSET DIRECTION (w.r.t. eye)	DESCENT TIME (sec)	CLOCK AND DATE
TEST DATA SERIES F										
S1	500	1	56	ON SIDE	4		8.50	0430	7.00	1338-03/05
S2	500	2	56	ON SIDE	3		7.42	0700	7.00	1343-03/05
S3	500	6	56	ON SIDE	3		8.25	0430	7.50	1348-03/05
S4	500	2	56	ON SIDE	3		6.75	0630	-	1403-03/05
S5	500	1	56	ON SIDE	3		6.25	0430	7.10	1404-03/05
S6	500	6	56	ON SIDE	3		5.67	0400	-	1406-03/05
						$\bar{O}$ =	7.14	$\bar{T}$ =	7.15	
						S_o =	1.12	S_t =	0.238	
						S_o^2 =	1.25	S_t^2 =	0.057	
						σ^2 =	26.01			

APPENDIX B_2 - CEL DATA

TEST SERIES A

SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	VERTICAL HEIGHT (ft)	OFFSET		TIME		DATE
				DISTANCE (ft)	DIRECTION (degrees)	DESCENT (sec)	CLOCK	
1000	11	24	0	3.75	305	3.7	1542	7/18
1000	13	24	0	1.50	338	3.5	1546	7/18
1000	11	24	0	1.42	295	3.7	1602	7/18
1000	13	24	0	2.75	170	---	1604	7/18
1000	14	24	0	2.08	358	3.8	1606	7/18
			$\bar{O}$ =	2.30	$\bar{T}$ =	3.68		
			S_o =	0.97	S_t =	0.130		
			S_o^2 =	0.94	S_t^2 =	0.016		
			$_o^2$ =	3.02				
1000	14	24	4	2.00	060	3.1	1007	7/18
1000	13	24	4	3.33	290	3.2	1011	7/18
1000	11	24	4	5.17	062	---	1015	7/18
1000	14	24	4	3.83	270	---	1051	7/18
1000	11	24	4	3.33	340	---	1054	7/18
1000	13	24	4	2.25	030	---	1056	7/18
1000	11	24	4	3.67	240	3.4	1516	7/18
1000	14	24	4	2.17	280	3.6	1519	7/18
1000	13	24	4	1.83	342	3.6	1522	7/18
1000	14	24	4	2.25	240	3.8	1540	7/18
			$\bar{O}$ =	2.98	$\bar{T}$ =	3.45		
			S_o =	1.07	S_t =	0.270		
			S_o^2 =	1.14	S_t^2 =	0.070		
			$_o^2$ =	4.96				
8500	4	24	0	3.67	215	---	1625	7/18
8500	4	24	0	3.25	215	2.6	1637	7/18
8500	1	24	0	3.08	100	2.6	1652	7/18
			$\bar{O}$ =	3.33	$\bar{T}$ =	2.60		
			S_o =	0.30	S_t =	0.000		
			S_o^2 =	0.09	S_t^2 =	0.000		
			$_o^2$ =	5.59				

SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	VERTICAL HEIGHT (ft)	OFFSET DISTANCE (ft)	OFFSET DIRECTION (degrees)	TIME DESCENT (sec)	TIME CLOCK	DATE
8500	1	24	4	2.67	040	---	1125	7/18
8500	4	24	4	1.08	030	---	1133	7/18
8500	4	24	4	4.25	175	---	1252	7/18
8500	4	24	4	3.50	210	---	1328	7/18
8500	4	24	4	3.08	180	2.7	1440	7/18
8500	4	24	4	3.67	228	2.5	1457	7/18
			$\bar{O}$ =	3.04	$\bar{T}$ =	2.60		
			S_o =	1.10	S_t =	0.140		
			S_o^2 =	1.21	S_t^2 =	0.020		
			σ^2 =	5.13				
8500	1	24	6	3.92	235	2.4	1707	7/78
			$\bar{O}$ =	3.92	$\bar{T}$ =	2.40		
			S_o =	0.00	S_t =	0.000		
			S_o^2 =	0.00	S_t^2 =	0.000		
			σ^2 =	7.68				
TEST SERIES B								
1000	13	56	0	4.50	050	8.2	0914	7/21
1000	12	56	0	4.42	255	8.2	0917	7/21
1000	14	56	0	6.33	300	7.8	1044	7/21
1000	11	56	0	9.67	280	7.9	1045	7/21
1000	14	56	0	5.00	330	8.1	1143	7/21
1000	15	56	0	7.33	145	8.2	1144	7/21
			$\bar{O}$ =	6.21	$\bar{T}$ =	8.07		
			S_o =	2.04	S_t =	0.180		
			S_o^2 =	4.17	S_t^2 =	0.030		
			σ^2 =	21.01				
1000	13	56	4	8.00	310	8.2	1052	7/21
1000	11	56	4	0.00	---	8.2	1150	7/21
1000	13	56	4	3.17	035	8.3	1256	7/21
1000	12	56	4	11.67	055	---	1258	7/21
1000	15	56	4	6.17	350	8.6	1300	7/21
			$\bar{O}$ =	5.80	$\bar{T}$ =	8.33		
			S_o =	4.47	S_t =	0.190		
			S_o^2 =	20.00	S_t^2 =	0.040		
			σ^2 =	24.83				

SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	VERTICAL HEIGHT (ft)	OFFSET		TIME		DATE
				DISTANCE (ft)	DIRECTION (degrees)	DESCENT (sec)	CLOCK	
1000	15	56	6	4.58	240	8.0	1046	7/21
1000	12	56	6	4.17	90	---	1049	7/21
1000	12	56	6	10.75	150	8.5	1146	7/21
1000	13	56	6	2.00	330	8.4	1148	7/21
1000	11	56	6	5.33	330	8.3	1252	7/21
1000	14	56	6	2.58	345	8.4	1154	7/21
			$\bar{O}$ =	4.90	$\bar{T}$ =	8.32		
			S_o =	3.13	S_t =	0.190		
			S_o^2 =	9.77	S_t^2 =	0.040		
			σ_o^2 =	16.08				
5000	8	56	0	10.50	030	6.2	----	7/21
5000	7	56	0	4.33	000	6.4	----	7/21
5000	6	56	0	10.75	175	6.1	1324	7/21
5000	10	56	0	5.83	030	6.8	1327	7/21
5000	8	56	0	9.92	000	6.7	1629	7/21
5000	6	56	0	5.92	060	6.8	1633	7/21
5000	7	56	0	2.58	090	6.4	1637	7/21
5000	10	56	0	11.42	350	6.5	1641	7/21
			$\bar{O}$ =	7.66	$\bar{T}$ =	6.49		
			S_o =	3.38	S_t =	0.260		
			S_o^2 =	11.45	S_t^2 =	0.070		
			σ_o^2 =	34.32				
5000	8	56	4	6.83	160	7.1	1334	7/19
5000	6	56	4	0.75	000	6.6	1341	7/19
5000	7	56	4	6.75	305	6.6	1343	7/19
5000	10	56	4	3.25	90	6.7	1345	7/19
5000	7	56	4	4.25	280	7.1	1426	7/19
5000	6	56	4	7.08	32	6.8	1429	7/19
5000	8	56	4	4.75	330	6.3	1432	7/19
5000	10	56	4	6.75	90	6.9	1435	7/19
			$\bar{O}$ =	5.05	$\bar{T}$ =	6.76		
			S_o =	2.25	S_t =	0.270		
			S_o^2 =	5.08	S_t^2 =	0.070		
			σ_o^2 =	14.98				

SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	VERTICAL HEIGHT (ft)	OFFSET		TIME		DATE
				DISTANCE (ft)	DIRECTION (degrees)	DESCENT (sec)	CLOCK	
5000	10	56	6	4.83	075	7.1	0921	7/21
5000	7	56	6	2.08	---	6.7	0925	7/21
5000	6	56	6	4.67	155	6.4	0929	7/21
5000	8	56	6	11.67	060	6.4	0933	7/21
5000	10	56	6	6.58	150	6.2	1054	7/21
5000	8	56	6	4.83	340	6.5	1056	7/21
			$\bar{O}$ =	5.78	$\bar{T}$ =	6.55		
			S_o =	3.23	S_t =	0.310		
			S_o^2 =	10.41	S_t^2 =	0.100		
			σ^2 =	21.02				
8500	1	56	0	10.08	015	5.3	1555	7/21
8500	4	56	0	2.75	300	5.6	1604	7/21
8500	3	56	0	8.00	320	5.6	1608	7/21
8500	2	56	0	1.17	180	5.3	1612	7/21
8500	1	56	0	1.00	230	5.7	1657	7/21
8500	2	56	0	4.50	90	---	1700	7/21
			$\bar{O}$ =	4.58	$\bar{T}$ =	5.50		
			S_o =	3.73	S_t =	0.190		
			S_o^2 =	13.95	S_t^2 =	0.030		
			σ^2 =	16.32				
8500	3	56	4	2.25	90	---	1416	7/21
8500	4	56	4	3.00	140	5.9	1423	7/21
8500	2	56	4	7.67	30	---	1426	7/21
8500	5	56	4	8.00	75	6.0	1429	7/21
8500	1	56	4	4.75	330	5.9	1432	7/21
8500	5	56	4	4.58	175	5.3	1530	7/21
			$\bar{O}$ =	5.04	$\bar{T}$ =	5.78		
			S_o =	2.36	S_t =	0.320		
			S_o^2 =	5.58	S_t^2 =	0.100		
			σ^2 =	15.04				

TEST SERIES C

SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	VERTICAL HEIGHT (ft)	OFFSET DISTANCE (ft)	OFFSET DIRECTION (degrees)	TIME DESCENT (sec)	TIME CLOCK	DATE
1000	12	88	0	1.75	---	13.5	0953	7/20
1000	11	88	0	5.58	350	12.9	0955	7/20
1000	14	88	0	3.25	000	13.5	1110	7/20
1000	15	88	0	8.33	020	13.2	1112	7/20
1000	12	88	0	8.75	035	13.7	1114	7/20
1000	11	88	0	3.58	335	12.5	1348	7/20
			$\bar{O}$ =	5.21	$\bar{T}$ =	13.22		
			S_o =	2.86	S_t =	0.450		
			S_o^2 =	8.17	S_t^2 =	0.200		
			σ^2 =	16.96				
1000	13	88	4	3.83	198	---	0927	7/12
1000	12	88	4	2.25	070	---	0930	7/12
1000	14	88	4	4.58	120	---	0932	7/12
1000	11	88	4	10.75	250	---	0935	7/12
1000	15	88	4	4.50	270	13.1	0938	7/12
1000	14	88	4	4.58	330	13.4	1036	7/12
1000	12	88	4	9.25	339	13.4	1039	7/12
1000	15	88	4	6.67	145	---	1042	7/12
1000	11	88	4	----	---	13.2	1046	7/12
			$\bar{O}$ =	5.80	$\bar{T}$ =	13.28		
			S_o =	2.89	S_t =	0.150		
			S_o^2 =	8.33	S_t^2 =	0.020		
			σ^2 =	20.47				
1000	12	88	6	12.08	320	---	1349	7/20
1000	14	88	6	1.00	335	12.9	1351	7/20
1000	15	88	6	6.08	300	12.8	1353	7/20
1000	13	88	6	8.08	020	12.8	1356	7/20
1000	12	88	6	7.17	245	12.8	1456	7/20
1000	12	88	6	4.24	023	13.1	----	7/20
			$\bar{O}$ =	6.44	$\bar{T}$ =	12.88		
			S_o =	3.73	S_t =	0.130		
			S_o^2 =	13.92	S_t^2 =	0.020		
			σ^2 =	26.55				

SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	VERTICAL HEIGHT (ft)	OFFSET DISTANCE (ft)	OFFSET DIRECTION (degrees)	TIME DESCENT (sec)	TIME CLOCK	DATE
5000	10	88	0	4.50	260	10.0	1346	7/20
5000	10	88	0	5.17	90	9.9	1620	7/20
5000	7	88	0	6.42	240	9.8	1622	7/20
5000	6	88	0	6.42	000	9.1	----	7/20
5000	7	88	0	4.67	270	9.2	0937	7/20
5000	8	88	0	5.75	180	9.1	0939	7/20
			$\bar{O}$ =	5.49	$\bar{T}$ =	9.52		
			S_o =	0.84	S_t =	0.430		
			S_o^2 =	0.71	S_t^2 =	0.180		
			σ^2 =	15.36				
5000	6	88	4	2.00	240	10.3	0937	7/20
5000	8	88	4	6.33	145	----	0940	7/20
5000	10	88	4	9.33	300	----	0944	7/20
5000	7	88	4	4.58	165	10.5	0947	7/20
5000	7	88	4	9.33	038	----	1116	7/20
5000	10	88	4	4.25	030	10.8	1119	7/20
			$\bar{O}$ =	5.97	$\bar{T}$ =	10.53		
			S_o =	2.94	S_t =	0.250		
			S_o^2 =	8.67	S_t^2 =	0.060		
			σ^2 =	21.43				
5000	7	88	6	8.33	280	10.2	1358	7/20
5000	6	88	6	4.42	030	9.9	1400	7/20
5000	10	88	6	11.75	035	10.1	1454	7/20
5000	7	88	6	5.50	120	11.0	1458	7/20
5000	6	88	6	2.83	270	----	1501	7/20
5000	8	88	6	6.50	140	9.9	1504	7/20
			$\bar{O}$ =	6.56	$\bar{T}$ =	10.22		
			S_o =	3.15	S_t =	0.450		
			S_o^2 =	9.94	S_t^2 =	0.210		
			σ^2 =	25.62				

SINKER SIZE (lbs)	SINKER NUMBER	WATER DEPTH (ft)	VERTICAL HEIGHT (ft)	OFFSET DISTANCE (ft)	OFFSET DIRECTION (degrees)	TIME DESCENT (sec)	TIME CLOCK	DATE
8500	1	88	0	3.17	210	---	0740	7/22
8500	2	88	0	7.33	252	---	0745	7/22
8500	3	88	0	4.75	300	---	0750	7/22
8500	4	88	0	4.83	085	---	0755	7/22
8500	5	88	0	11.75	050	---	0759	7/22
8500	1	88	0	6.33	000	8.2	0931	7/22
			$\bar{O}$ =	6.36	$\bar{T}$ =	8.20		
			S_o =	3.00	S_t =	0.000		
			S_o^2 =	9.02	S_t^2 =	0.000		
			σ^2 =	23.98				
8500	2	88	4	4.42	030	9.0	1306	7/11
8500	4	88	4	4.17	095	8.9	1312	7/11
8500	3	88	4	8.50	285	9.2	1319	7/11
8500	1	88	4	11.50	200	---	1325	7/11
8500	5	88	4	5.50	340	9.2	1330	7/11
8500	3	88	4	7.75	210	---	1545	7/11
8500	1	88	4	3.00	260	---	1550	7/11
8500	5	88	4	6.33	162	---	1553	7/11
8500	4	88	4	9.75	092	8.8	1556	7/11
			$\bar{O}$ =	6.77	$\bar{T}$ =	9.02		
			S_o =	2.82	S_t =	0.180		
			S_o^2 =	7.94	S_t^2 =	0.030		
			σ^2 =	26.44				
8500	2	88	6	8.08	190	8.0	0948	7/22
8500	5	88	6	7.25	330	8.2	0957	7/22
8500	5	88	6	9.25	060	---	1054	7/22
8500	5	88	6	12.50	310	8.0	1058	7/22
8500	2	88	6	6.42	280	8.1	1103	7/22
8500	3	88	6	4.58	300	---	1107	7/22
			$\bar{O}$ =	8.01	$\bar{T}$ =	8.08		
			S_o =	2.70	S_t =	0.100		
			S_o^2 =	7.31	S_t^2 =	0.010		
			σ^2 =	35.15				

APPENDIX C

As reported in Section 3.3, ANOVA's were performed on the circular normal σ's, and also on the offsets (ranges), as a check. The results agreed well, as expected.

The mathematical nature of the $\bar{\sigma}$'s presented a slight problem in performing the ANOVA's: Each ANOVA block contains replications, so that the variance within the block may be calculated. Thus, at a given setting of sinker size, water depth, etc., there were several drops, usually about five. Normally, a mean of five observations would be tested, and the within-block variance is the variance of the five observations from that mean. Unfortunately, the calculation of σ in Section 3.3, although based on n observations, cannot be written as a mean of n numbers. Recall:

$$\sigma = \frac{\sqrt{\Sigma\left(X^2 + Y^2\right)}}{\sqrt{2n}}$$

Therefore, there is no natural way to calculate the within-block variance when σ is the ANOVA block entry. It is desirable, therefore, to find an appropriate "standard deviation" σ' which is an arithmetic mean of n numbers. There are several possible solutions to this problem:

1. The ANOVA could be performed on the variance instead of the standard deviation. The variance is:

$$\sigma^2 = \frac{\sum\left(\frac{X^2 + Y^2}{2}\right)}{n}$$

which is the mean of the n numbers $(x^2 + Y^2)/2$. However, an ANOVA should be performed on a variable whose distribution is as close to normal as possible. The "squaring" effect of the variance would make the ANOVA's unreliable; the analysis could show an interaction effect when in fact none exists. Therefore, this approach was not used.

2. The ANOVA could be performed on the variable

$$\sigma' = \frac{\sum\sqrt{\frac{X^2 + Y^2}{2}}}{n}$$

Here σ' is derived by calculating the sample standard deviation for each single observation and then taking the mean of these n deviations.

Note that:

$$\frac{\sum x^2+y^2}{2n} = \left(\frac{\sum\sqrt{\frac{x^2+y^2}{2}}}{n}\right)^2 + 1/2\ \frac{\sum\left(\sqrt{x^2+y^2} - \frac{\sum\sqrt{x^2+y^2}}{n}\right)^2}{n}$$

i.e. $$\sigma^2 = (\sigma')^2 + \frac{1}{2}\ \frac{\Sigma(r-\bar{r})^2}{n} .$$

or, equivalently, if σ_r = the standard deviation of the ranges about the mean range,

$$\sigma^2 = (\sigma')^2 + 1/2\ (\sigma_r)^2$$

If the sinker is very directional, σ_r will be small compared to σ and σ', which will therefore be nearly equal. This means that the NSWC results, which are more complicated than the CEL results and involve directional sinkers, experience little loss in accuracy due to the use of σ'.

Also note that σ' is very closely related to the range:

$$\sigma' = \frac{\sum\sqrt{\frac{x^2+y^2}{2}}}{n} = \frac{1}{\sqrt{2}}\ \frac{\sum\sqrt{x^2+y^2}}{n} = \frac{\text{mean range}}{\sqrt{2}} .$$

Thus, performing an ANOVA using this "mean standard deviation" σ' as the block entry is equivalent to performing the ANOVA using the mean ranges. This approach was used for all ANOVA procedures.

3. The ANOVA could still be performed using σ as the block entry, even though σ is not a mean of n numbers. In this case the highest cross product (the interaction of all factors) is used as an estimate of the within-block variance. This procedure assumes, of course, that there is no highest-order interaction among the factors, which may not always be justified. However, this approach was also used in the ANOVA's, and almost all the results agree with those obtained by procedure #2 above.